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Experimental monthly long-range forecasts for the United Kingdom

Part I. Description of the forecasting system

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Summary

Although a public service of long-range forecasts for the month ahead for the United Kingdom ceased at the end of 1980, regular long-range forecasts have continued to be made, together with a restricted commercial consultancy scheme. A summary is given of the major changes in procedure and technique that have occurred since the public service ceased, together with an indication of the scientific ideas that currently guide long-range forecasting research. Companion papers by Murphy and Palmer (1986) and Folland *et al.* (1986) provide a detailed description of dynamical techniques applied to long-range forecasting and an assessment of the skill of the long-range forecasts issued since 1964.

1. Introduction

A public service of twice-monthly long-range forecasts for one month ahead began with a forecast for December 1963 and ceased after 17 years with the forecast for mid-December 1980 to mid-January 1981. A service of experimental seasonal (3 months ahead) forecasts for selected industrial concerns also ceased with the forecast for the winter of 1980/81. However, forecasts have continued to be made every half month for the 30 days ahead on an experimental basis, without a break. The forecasts are still sent to a limited number of commercial and corporate users if it is thought they may be able to gain cumulative benefits from a low average level of forecast skill over an extended period. Shortage of staff currently demands that the total number of users is kept small.

Analogue (chart-matching) techniques no longer form part of the process for forecasting atmospheric circulation; indeed two relatively new techniques, a regression technique and a more important technique using advanced multivariate statistics, now provide almost the only statistical input to these forecasts. The contribution of medium-range dynamical numerical weather forecasts has increased as they have become more reliable and available for longer periods ahead. An important activity of the forecaster is, therefore, the imaginative combining of dynamical and statistical techniques, although the impact of truly long-range dynamical forecasts has so far been fairly small. One result of the work is an increasing need to distinguish between the contributions from medium- and long-range techniques to the skill over the month as a whole.

2. Predictability — what should be predicted?

Variations of atmospheric circulation occur on all time-scales; in mid-latitudes, regional circulation patterns (space scale 4000–10 000 km) tend to group into persistent 'spells' or regimes containing one basic pattern that typically lasts for 10 days to 1 month with only short breaks. Sometimes, however, extended 'chaotic' periods occur when a coherent circulation regime is less apparent. Blocking is an example of a type of coherent spell whose dynamics are now starting to be revealed, see for example Shutts (1983). The majority of spells near the United Kingdom tend to be associated with other recognizable circulation regimes. Examples are: persistently westerly types with large day-to-day variability; persistently cyclonic types often associated, in the longitude sector of the United Kingdom, with weak tropospheric flow and mid-tropospheric jets to the north and south; and anticyclonic westerly types associated with a broad and persistent medium amplitude mid-tropospheric ridge (such as occurred frequently in the 'drought' year of 1975/76).

Fig. 1 illustrates two extreme examples of spells lasting about 3 months (Legg, personal communication). Figs 1(a) and (b) show the location of the average position of the maximum speed of the jet stream at 500 mb in each 5-day period (pentad) between June and August for 1983 and 1985 respectively. Averaging the 500 mb height data removes variations due to the passage of individual depressions. Lines have been drawn where the mean maximum speed of the jet exceeded about 50 knots. In general the centres of depressions will pass a few hundred kilometres to the north of, but approximately parallel to, the lines drawn in Fig. 1. Clearly the jet stream paths near the United Kingdom were systematically different in the two summers, most pentads showing a more southerly jet position in 1985 than any in 1983. So the contrasting characters of the two summers (especially over Scotland) were not the net, almost chance, result of a minority of exceptionally different pentads. Such clear inter-annual contrasts at specific times of the year are quite common, especially for periods of a few weeks. This characteristic of the atmosphere strongly hints at the sometimes (but not invariably) dominant role of mechanisms that control weather near the United Kingdom on much larger time-scales than those of individual baroclinic disturbances. Understanding and then forecasting the behaviour of these low-frequency weather processes can be seen as a central task of the researcher into long-range forecasting.

In numerical forecasting, it is widely accepted that there is, in principle, a limit to the time ahead that the skilful forecasting of *instantaneous* states of the weather observed at any point is possible. This 'limit of deterministic predictability' is thought to lie 2–3 weeks ahead in middle latitudes. The long-range forecaster must therefore have a basically different practical objective — to try to predict time and space averages of weather events and if possible forecast the statistical character of weather variability over a region and over a time interval. A further difference from medium-range forecasts, at least up to the present, is that the long-range forecaster concentrates on forecasting anomalies (deviations) from the climatological mean state for a particular time of year and region. The climatological mean can be calculated in advance and made available to the users; the task of forecasting the deviations from this mean is in principle simpler than forecasting the absolute values. This is especially true of patterns of surface weather, where the anomaly patterns tend to have a much larger spatial scale than those of their absolute values. Examples are patterns of monthly-mean temperature and rainfall over the United Kingdom. This approach reduces the number of degrees of freedom required to be forecast and is especially helpful in statistical forecasting.

There is, of course, no guarantee that these larger scales in space and time are really predictable beyond the deterministic limit. However, they tend to be more influenced by the 'slower' internal atmospheric features such as the upper tropospheric long waves, by persistent anomalous large-scale patterns of sea surface temperatures (Mansfield 1986, Palmer and Mansfield 1984, Palmer and Sun 1985), soil moisture (Rowntree and Bolton 1983) and snow or ice cover, and perhaps by slowly moving

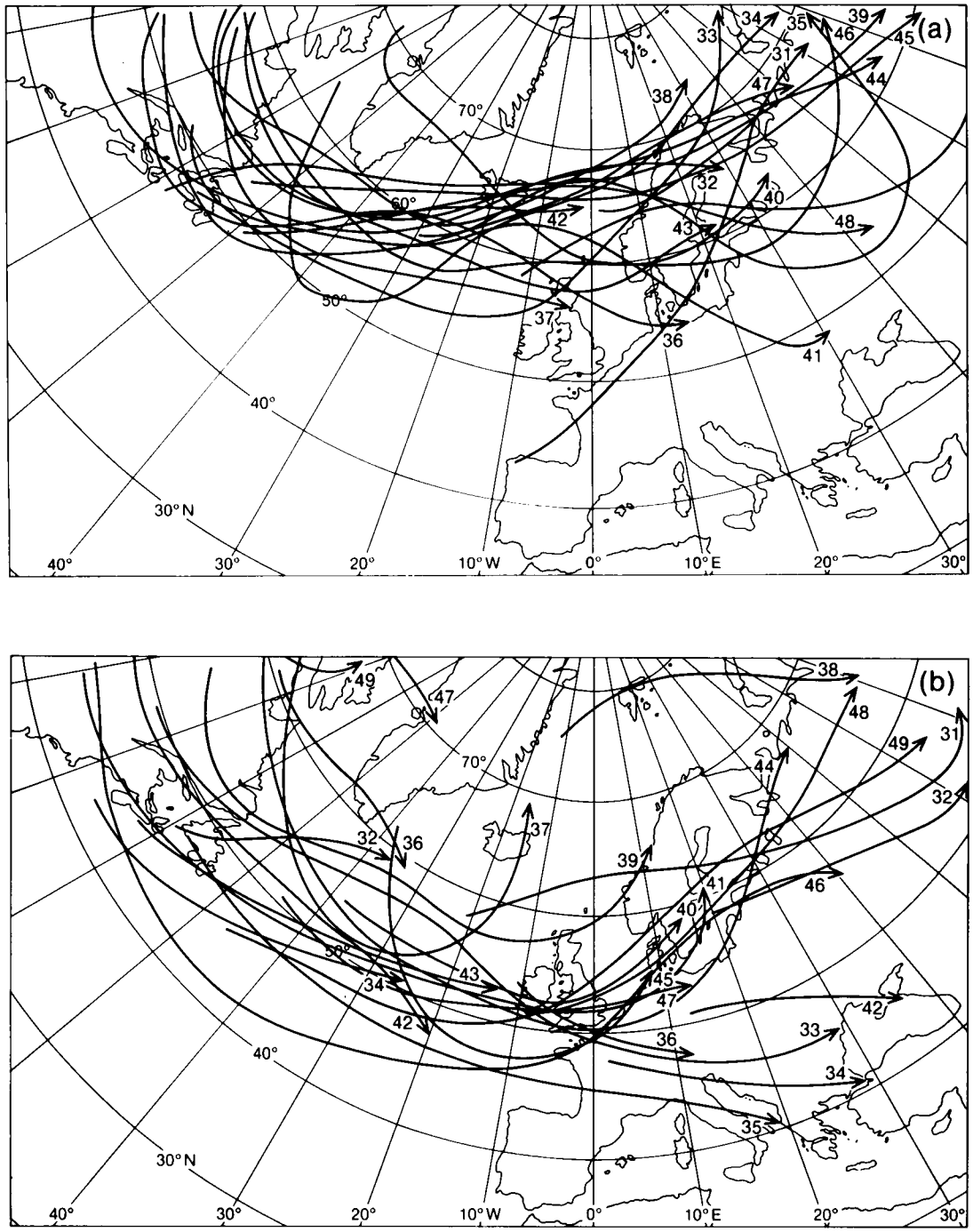


Figure 1. Position of 5-day (pentad) mean maximum jet stream speeds (> 50 kn) at 500 mb during June, July and August for (a) 1983 and (b) 1985. The arrows indicate the direction of the mean flow and the figures give the pentad number (e.g. 41 refers to the 41st five-day period into the year).

or varying patterns of deep tropical atmospheric convection (Weickmann *et al.* 1985). A real hope for useful predictability comes from the many studies of the variability of large-scale time-averaged (e.g. monthly-mean) atmospheric circulation patterns. A large proportion of the total non-seasonal variance seems to be caused by a surprisingly small number of patterns (Craddock and Flood 1969, Blackmon *et al.* 1984, Barnston and Livezey 1985), even if different analysts do not always agree on the same patterns. The patterns so far identified may not reflect coherent dynamical processes (though some theories exist, e.g. Simmons *et al.* (1983)), but the studies do hint that the number of degrees of freedom that need to be forecast with skill before long-range forecasts become truly useful may be much less than is sometimes suggested, as for example by Tapp (1984). Another quite hopeful sign is that moderately useful regional monthly temperature forecasts, especially for certain seasons, have been issued in recent years (see for instance Folland *et al.* (1986) and Kalnay and Livezey (1985) who discuss forecasts issued by the National Weather Service of the USA).

3. Potential value of long-range forecasts

The user of long-range forecasts is often interested in how long a spell of weather that has already started will last, what the following spell will be like and approximately when it will start. Substantial fluctuations of temperature (from the climatological average) are often involved in the change from one weather spell to the next. Thus large variations of temperature (about the climatological average) occur on time-scales of weeks or more. The relative strengths of these variations are illustrated using a power spectrum analysis of daily Central England Temperature (Fig. 2) for 1936–85 from which the long-term average for each day has been removed. The variance of any range of frequency is given by the corresponding area under the spectral curve. The spectrum is in fact an average of ten individual spectra calculated for the non-overlapping 5-year periods between 1936 and 1985, and uses a recently

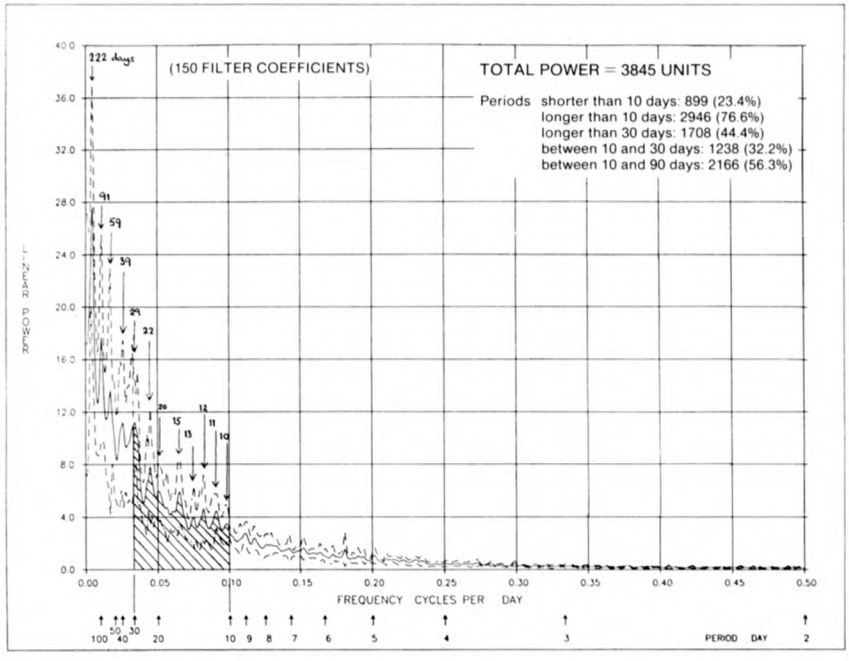


Figure 2. Mean maximum entropy method power spectrum of daily Central England Temperature anomalies 1936–85 with ±1 standard deviation marked as dashed lines.

homogenized daily Central England Temperature data set (Storey *et al.* 1985). The variance on short- and medium-range time-scales (2–10 days) is rather less (897 units) than that on time-scales of 10–30 days (1238 units) and only about 40% of that on the long-range, if periods up to, say, 90 days are included. Hence there is appreciably more variability of Central England Temperature anomalies to predict on long-range than on shorter-range time-scales. Gilchrist (1986) discusses this further.

4. Structure of the monthly forecasts

Fig. 3 shows the 10 districts covering the United Kingdom for which forecasts of surface weather anomalies are issued, and also the location of 149 climatological stations, having mostly long good-quality records, which are now used to help assess the skill of surface weather anomaly forecasts. A discussion of the scientific basis for the choice of these climatological stations is given in Folland and Shackleton (1984) and Folland (1983). The districts range in area from about 13 000 km^2 to about 40 000 km^2. Forecasts for the month ahead, updated every half month, are issued for each district.

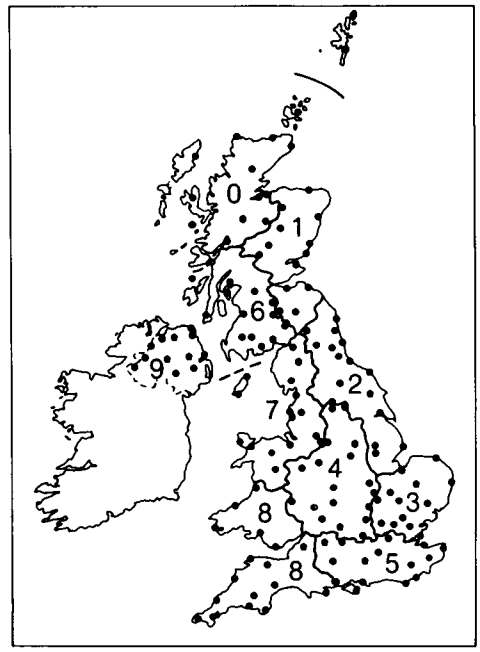


Figure 3. Positions of daily weather monitoring stations and forecast districts.

Fig. 4 shows how a typical forecast is structured (February 1986 was chosen because it was an extremely interesting month, being one of the coldest Februarys recorded). The average pressure at mean sea level (PMSL) pattern near the United Kingdom is forecast separately for the first 5 days of the month ahead ('medium range'), the remainder of the first half month ('mid-range') and the second half month ('long range'). These forecast patterns are permanently recorded and from them the best estimate and probability forecasts of temperature anomaly and percentage of average rainfall (henceforth called rainfall percentage) are constructed for each district. The anomalies are expressed at present as departures from a 1951–80 average. Fig. 5 shows the subsequently observed PMSL patterns and district mean surface weather anomalies. The best-estimate forecasts are currently expressed in meteorological units (in °C and as a rainfall percentage) for each of the three periods. In the telex message that is

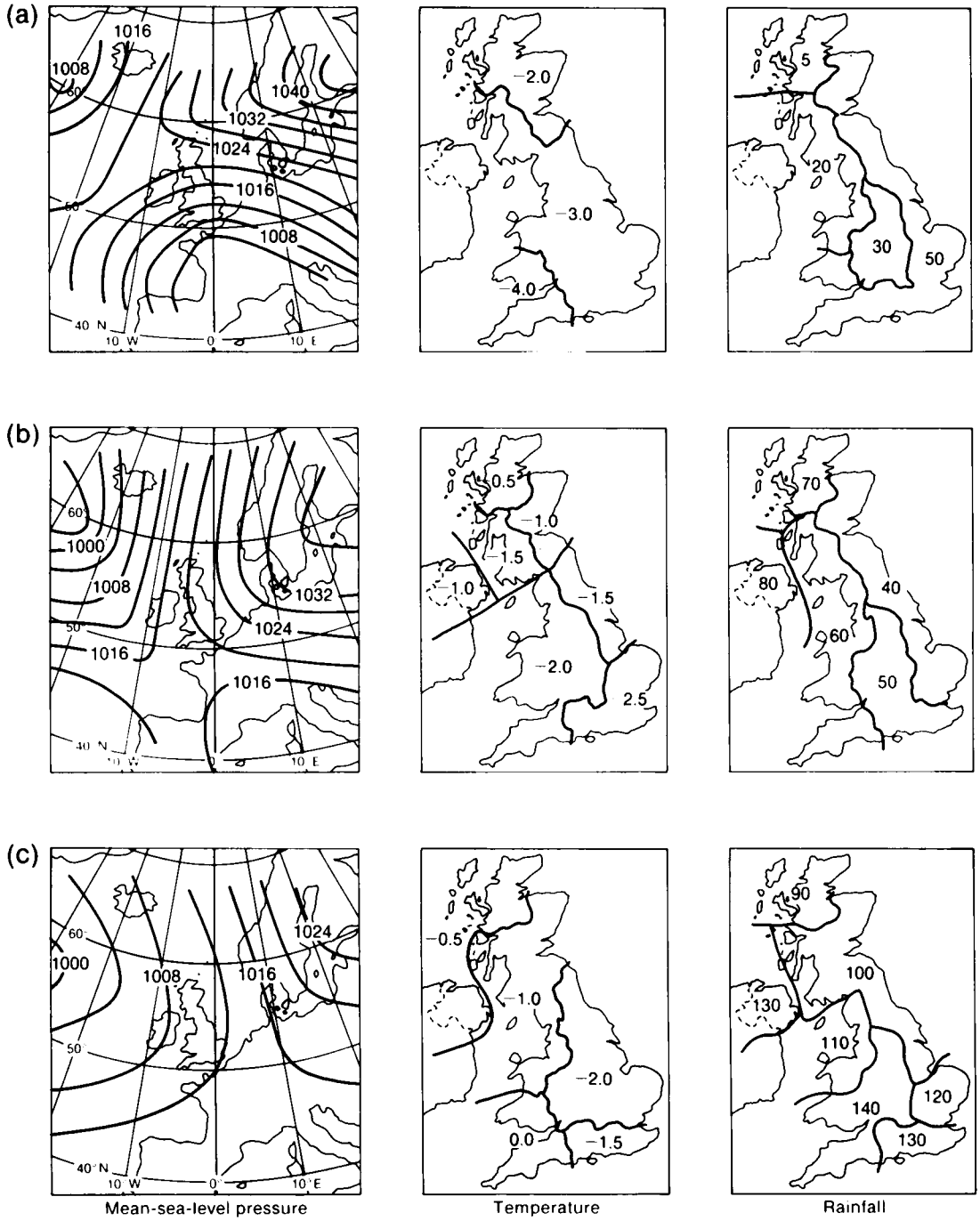


Figure 4. Typical example of a long-range forecast of pressure (mb), temperature anomaly (°C) and rainfall (% of normal) for (a) 1–5, (b) 6–15 and (c) 16–28 February 1986.

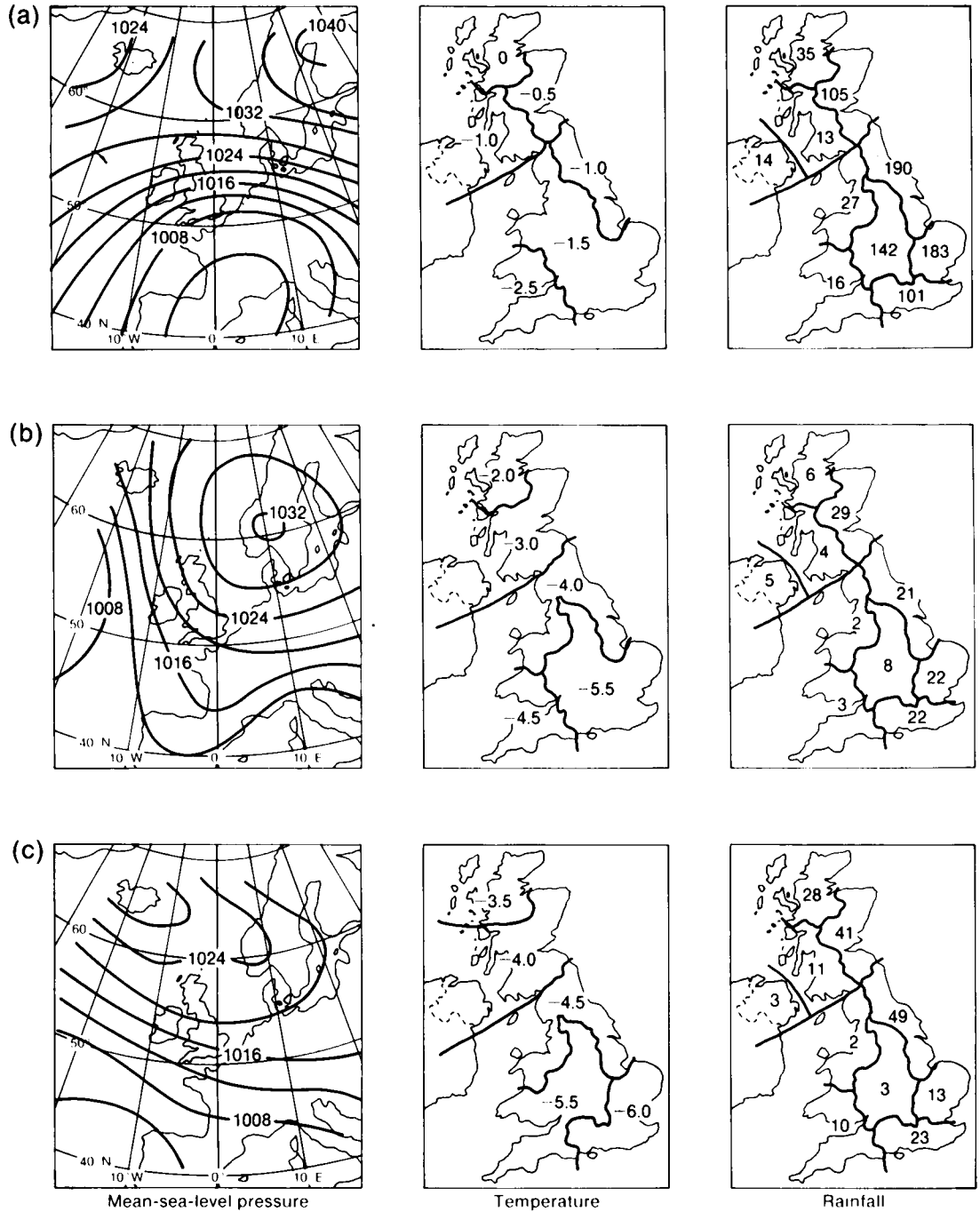


Figure 5. Observed presure (mb), temperature anomaly (°C) and rainfall (% of normal) data for (a) 1–5, (b) 6–15 and (c) 16–28 February 1986.

currently issued to recipients (see Fig. 6, which gives the February 1986 forecast, issued on 31 January) the medium- and mid-range periods are grouped together. Fig. 6 also shows that probability forecasts of temperature and rainfall are made for the month as a whole. The temperature forecasts for each district consist of a set of five probabilities, one for each of five climatologically equiprobable ranges of observed temperature for the given month. These are known as 'quints' and each has a long-term probability of occurrence of 0.2. Similarly the rainfall probability forecast consists of a set of three probabilities, one for each of three climatologically equiprobable ranges of observed rainfall, known as 'terces' (long-term probabilities of occurrence of 0.333).

FORECAST FOR THE PERIOD COMMENCING..1/2/86.....ENDING..28/2/86.....

PART 1 BEST ESTIMATE FORECASTS:

TEMPERATURE(DEGREES C) AS A DIFFERENCE FROM NORMAL AND
RAINFALL AS A PERCENTAGE OF NORMAL FOR EACH DISTRICT

(1) FIRST 15 DAYS

DISTRICT	0	1	2	3	4	5	6	7	8	9
TEMP.	-1	-1.5	-2	-2.5	-2.5	-2.5	-2	-2.5	-2.5	-1.5
RAINFALL	50	45	45	45	45	50	45	45	55	60

CONFIDENCE: E

(2) REMAINDER OF PERIOD

DISTRICT	0	1	2	3	4	5	6	7	8	9
TEMP.	-0.5	-1	-2	-2	-2	-1.5	-1	-1	0	-0.5
RAINFALL	90	100	100	120	140	130	100	110	140	130

CONFIDENCE: E

PART 2 PROBABILITY FORECASTS FOR THE WHOLE PERIOD.(TEMP. AND RAINFALL)

TEMPERATURE PERCENTAGE PROBABILITY:

	MUCH BELOW AVERAGE	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE	MUCH ABOVE AVERAGE
DISTRICTS: 0,1,9	20	30	25	15	10
2,3,4,5,6,7,8	35	25	20	15	5

RAINFALL PERCENTAGE PROBABILITY:

	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE
DISTRICTS: 0,1,2,6,7	40	35	25
3,4,5,8,9	30	40	30

STRONG WIND EXPECTATION:

Average

DESCRIPTION OF WEATHER EXPECTED DURING THE PERIOD.

Much of the month will be cold or very cold and rather dry.
It is expected to become much wetter and milder in the last week

OVERALL CONFIDENCE: E : © CROWN COPYRIGHT

ORIGIN: MET O 13 BRACKNELL DATE/TIME
ERT: 2685 TELEX 849801
THIS FORECAST IS NOT TO BE QUOTED WITHOUT REFERENCE 31Jan/1640
TO THE ORIGINATORS.

Figure 6. Example of the telex forecast message issued to users.

An important part of the issued forecast is a statement of the confidence that the forecasters express in the forecast at the time it is issued. This is expressed in principle on a scale from 'A' (highest confidence) to 'E' (lowest confidence) but the state of the art means that only the range from 'C' to 'E' is used at present. 'C' (most confident) is chosen if the various forecasting techniques are in broad agreement and the recent history of the skill of the forecasts is better than usual, especially the skill of the atmospheric circulation forecasts. 'E' represents a difficult forecast where synoptic judgement and more general considerations were prominent because of the strong disagreements between the forecasts given by the different techniques. The 'sharpness' of the probability forecasts is set by the confidence level in a subjective but predetermined way; thus a 'C' forecast would allocate a much higher probability to the most probable or 'best estimate' forecast quint or terce category than would an 'E' forecast. A general description of expected marked changes of weather type and the timing of the changes is added, together with a statement about the expected windiness of the month since one user is mainly interested in this information. It is important to remember that current statistical forecasting methods only forecast fields of PMSL, and that the temperature anomaly and rainfall percentage forecasts are inferred from them (see Section 5).

It should be noted that, whereas before 1981 the best-estimate temperature quint and rainfall terce forecasts were chosen directly, largely from the analogue forecasting techniques, they are currently automatically derived from the forecast temperature anomalies and rainfall percentages.

5. Techniques used to make the forecast

(a) *Statistical techniques for predicting PMSL patterns*

Cessation of the public service in long-range forecasts at the end of 1980 was accompanied by a substantial reduction of staff effort, so non-automated, labour-intensive, statistical techniques were set aside and only the most promising, largely automated, techniques retained.

The need to develop a new approach to statistical long-range forecasting was recognized in the Synoptic Climatology Branch of the Meterological Office in the mid-1970s. Long-range forecasts are always likely to be fundamentally probabilistic in nature and not truly deterministic, so a statistical approach that is deliberately designed to make forecasts of the probabilities of a range of possible future circulation patterns was felt to be a way forward. One such approach (not necessarily the best one in the long term) uses a multivariate statistical technique called linear discriminant analysis, and is the basis for the multivariate statistical forecasting technique (MVA) which is now the backbone of the UK statistical forecasting effort. It is described in detail by Maryon and Storey (1985), and by Folland and Colman (1986) who also provide recent tests of its skill. A fundamental discussion of MVA is also provided by Gilchrist (1986).

Briefly, MVA uses linear 'discriminant' equations derived from about 30 years of post-war data to forecast separately the probabilities of a predefined set of half-monthly mean PMSL patterns ('clusters') covering the North Atlantic and Europe in each half month of a monthly forecast using recently observed values of a set of atmospheric and sea surface temperature (SST) predictor variables. The atmospheric predictors consist of recent states of the lower troposphere in the northern hemisphere (north of 20°N), also averaged over half months, which are measured in the form of the strengths (eigenvector coefficients) of a set of covariance eigenvector patterns of 1000–500 mb thickness and PMSL. The set of regionally-averaged SST predictors consists of temperature anomalies averaged over the month preceding the forecast month in 15 key ocean regions. Examples of the eigenvectors are shown in Fig. 7 (adapted from Maryon and Storey (1985)) and the 15 SST predictor regions are shown in Fig. 8. The choice of region 2, for example, was guided by the pioneering work of Radcliffe and Murray (1970).

The use of eigenvectors is a method of describing past atmospheric fields in terms of statistically independent component fields each of which captures a part of the total variations of the past fields. Their validity as a representation of the atmosphere in the prediction step of a statistical forecasting model rests heavily on their ability genuinely to provide some predictive skill; the prediction will depend on the strengths of the eigenvectors deduced from recently observed data. Covariance eigenvectors of atmospheric anomalies provide the most straightforward mathematical representation of this type. If some of the eigenvectors represent dynamically coherent modes of atmospheric variation, the chances should be higher that the eigenvectors will have predictive skill. There is increasing evidence that the eigenvectors used here do have some predictive skill but may not provide the best method of representing dynamically coherent atmospheric patterns (Barnston and Livezey 1985 and Richman 1986). More complex forms of eigenvector analysis may be better; if so, the main advantage of eigenvectors, i.e. their ability to provide (nearly) statistically independent predictor patterns, is sufficiently great to make further investigation of this complex topic well worth while.

In MVA, the atmospheric eigenvector predictor strengths are currently measured separately over some or all of the four consecutive half months preceding the forecast period. Fig. 9 shows samples of

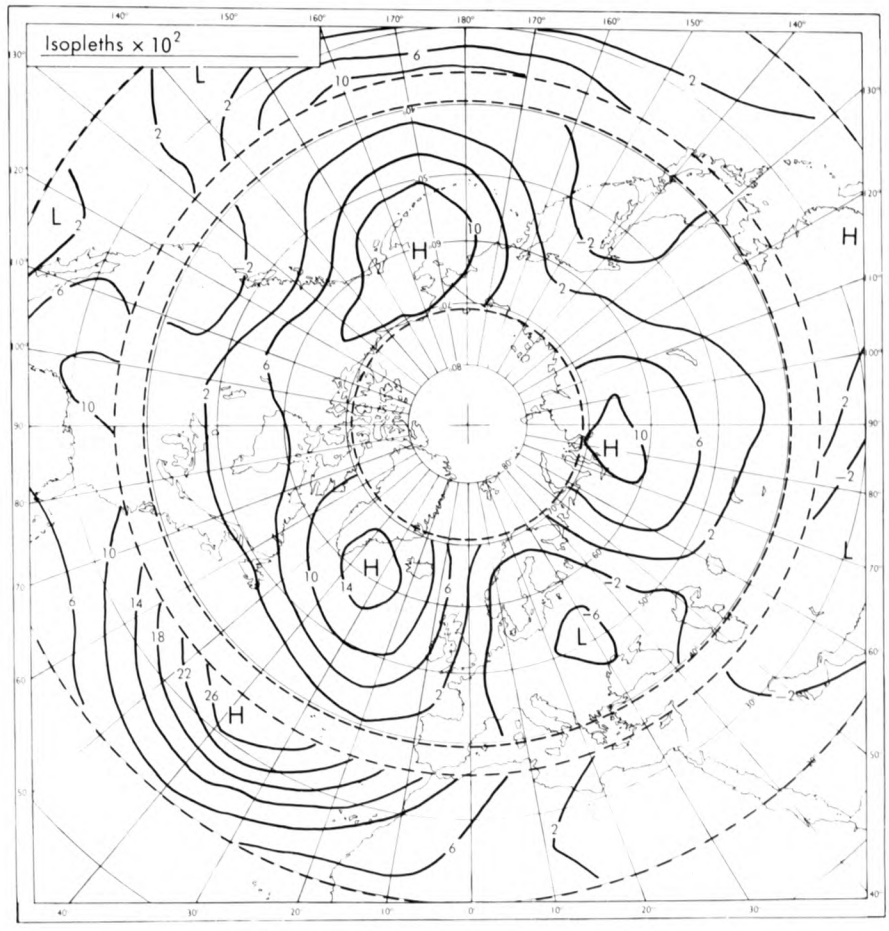


Figure 7. Sample predictor eigenvectors (standard dimensionless units): the second eigenvectors of both the northern and southern annuli of the northern hemisphere half-monthly mean-sea-level pressure for the pre-winter season (November–December).

the cluster patterns (for winter) whose probabilities (the 'predictands') are predicted in each forecast. The patterns are expressed here in the form of anomalies of PMSL calculated from a 1951–70 average.

The linear discriminant forecasting equations are created separately from historical data for the first and second half months of the forecast, and also for each of six 'natural' seasons, each two months long (i.e. January–February etc.). Special tests are used to ensure that only the most discriminating predictors are retained. The (predefined) cluster patterns change with the natural season but at present are always six in number in a given season. They do not occur equally often in the long run so their long-term probability of occurrence has to be estimated. It is assumed though that every half month can be classified into one of these clusters (see Maryon and Storey (1985) for details). Thus MVA consists of 12 similarly structured models each using a differently formulated set of linear discriminant prediction equations.

A second (regression) stage is currently used to 'fine tune' the forecasts of the most likely clusters, otherwise in each half month there are only 6 possible patterns to choose the forecast from. The regression equations contain a selection of similiar predictor variables as do the linear discriminant equations; however a few extra atmospheric predictors are included. Their purpose is to predict

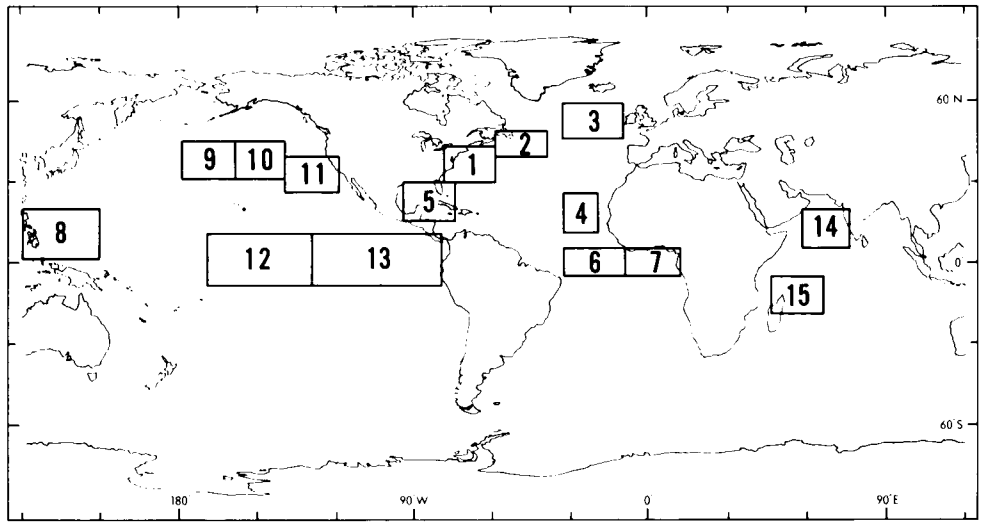


Figure 8. The 15 sea surface temperature areas currently used by the multivariate forecasting technique.

relatively small modifications to the most probable cluster patterns. This is done by predicting modest changes to the strengths of the most important eigenvectors that are used to represent each cluster pattern. In this way, modified PMSL patterns are created from the clusters; their probabilities of occurrence in the forecast period are assumed to be that of those clusters.

'Step-wise' statistical testing techniques are used to identify the most skilful predictors from those available in both the discrimination and regression stages; currently, this information is derived from a period of post-war data. Thus only a fraction of the predefined predictors are used in practice, and it is possible, for example, for a linear discriminant equation to contain few or none of the 15 'candidate' SST predictors.

In recent years, a range of the most skilful linear discriminant models has been used in practical forecasting, each containing a slightly different set of predictor variables. This approach provides an ensemble of sets of probability forecasts of the six clusters and therefore, as a by-product, of their 'tuned' (regressed) versions (Gilchrist 1986).

The ensemble approach considerably increases the information available from MVA; for example, the stability of the forecast probabilities can be assessed as the formulation of the linear discriminant equations is progressively altered by adding and subtracting variables. This particular use of an 'ensemble' of forecasts differs from that described by Murphy and Palmer (1986) during dynamical forecasting; in MVA the formulation (though not the basic structure) of the statistical model is progressively changed whereas Murphy and Palmer progressively change the initial data (equivalent to changing the MVA predictor strengths).

The only other statistical technique currently in use is the surface pressure eigenvector regression (SPEVR) (Maryon 1979). SPEVR is quite similar to the regression step of MVA but the predictors consist only of half-monthly mean covariance eigenvectors of PMSL. These are defined over much of the northern hemisphere and can include eigenvectors whose strengths are measured as much as one year before the forecast period. The predictands are the strengths of sets of covariance eigenvectors of PMSL anomalies over the North Atlantic and Europe defined over half months. There are two versions of SPEVR in each natural season (as with MVA), the first for one half month ahead and the second for two half months ahead. SPEVR is only capable of producing a single 'best estimate' PMSL pattern

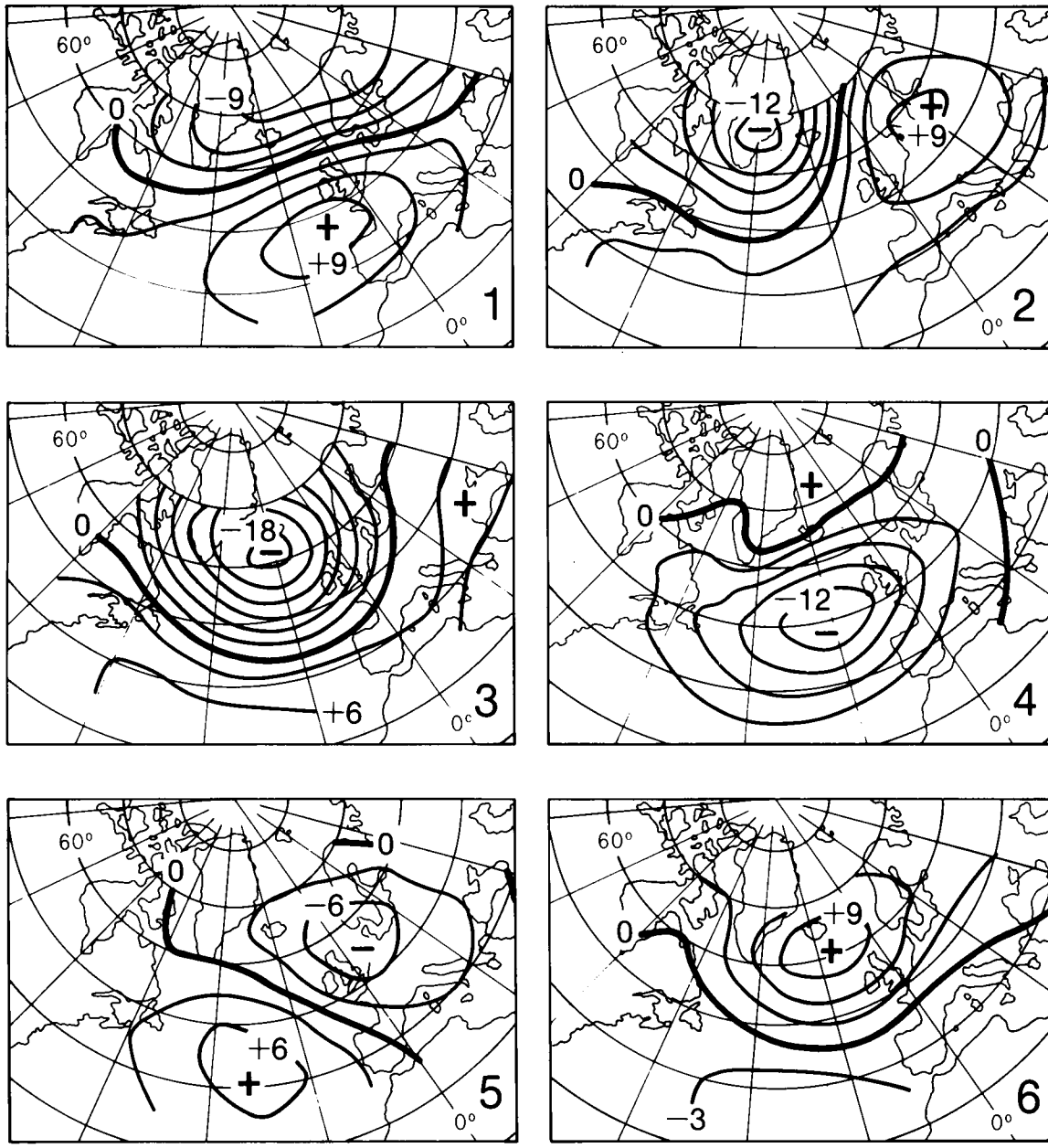


Figure 9. Mean-sea-level pressure anomaly patterns (mb) for the 6 clusters of the winter season (January–February), calculated from a 1951–70 average.

forecast. The ensemble approach is not used with SPEVR at present as staff resources have not been available to develop it. Maryon concluded that it was better to use a recent, post-war, historical period to construct the SPEVR prediction equations than a much longer historical period. Kates and Folland (1985) came to a similar conclusion when testing the skill of MVA. So SPEVR is currently based on historical data observed between 1950 and 1974. MVA, which has had much more attention, now uses data from 1949 to 1983 to construct its linear discriminant prediction equations.

(b) *Dynamical techniques in real-time long-range forecasting*

Dynamical long-range forecasting techniques have not yet made a large real-time impact, though the Meteorological Office 5-level general circulation model has in the past been used with some skill in winter (Mansfield 1986). Recently, occasional real-time use has been made of ensembles of forecasts from an 11-level general circulation model (Murphy and Palmer 1986). On the other hand, there has been a marked increase in the use of operational medium-range numerical weather forecasts; since December 1982 these have been available from the European Centre for Medium Range Weather Forecasts to day 10 of the medium-range period (usually day 8 or 9 of the long-range forecast). During days 1–5 of the long-range forecast the Meteorological Office 15-level model forecasts are usually available (almost always to day 4). At present both centres provide numerical forecasts of similar (and increasing) skill for the period for which they overlap. Differences between the numerical forecasts on individual occasions can, in conjunction with the statistical forecasts for the first half month ahead, be useful in judging the most likely developments during the mid-range period.

6. Derivation of district temperature and rainfall forecasts from PMSL forecasts

This aspect of long-range forecasting has probably changed most in the last 3–4 years. The recent availability of a reasonably long series of daily data of district averages of temperature and rainfall (commencing in 1951) has allowed fairly objective methods of deducing the district anomalies to be used, though judgement still plays a part.

(a) *Forecasts of rainfall percentage*

Two methods are now used. The first-guess forecast uses regression relationships between half-monthly mean rainfall anomalies and the PMSL calculated for the period 1951–85 for each district and calendar half month. Some smoothing of the regression relationships is carried out between adjacent half months (Legg, personal communication). Fig. 10 shows four of the regression lines, with their correlation coefficients, for south-west England. Over the medium-range period the judgement of the forecasters plays a dominant role, and these relationships only provide an approximate guide. The second-guess forecast of rainfall (in the mid-range or long range) is provided by an automatic search for historical PMSL patterns closely matching the forecast PMSL pattern just chosen (the 'matching technique'). The patterns are chosen from the same, or the two adjacent calendar half months observed since 1951; earlier years cannot yet be looked at as no analysed district mean climate data is available at present. The matching criteria include the similarity in PMSL values at four grid points around the United Kingdom and an index that provides a simple description of the forecast pattern shape (cyclonic westerly, anticyclonic, etc.). The forecasters then choose the 'best' pattern or patterns from these and read off the district rainfall percentages observed in the half months concerned. Judgement is used to combine the rainfall forecasts provided by the above methods for a given district.

Fig. 11 gives an example of the above procedure and shows the location of the four grid points. The two half-monthly mean PMSL fields, with their associated district mean rainfall anomalies, that were found to be most similar to the PMSL pattern forecast for 6–15 February 1986 (Fig. 4) are shown; these

were the second halves of February 1972 and February 1981. The fields were selected from all the half-monthly fields since 1951 that were observed in the first half of February or in the adjacent half months, i.e. the second halves of both January and February. The fact that the period of interest in 1986 is only 10 days long and the 'matching' fields are 15-day averages is not considered a serious problem.

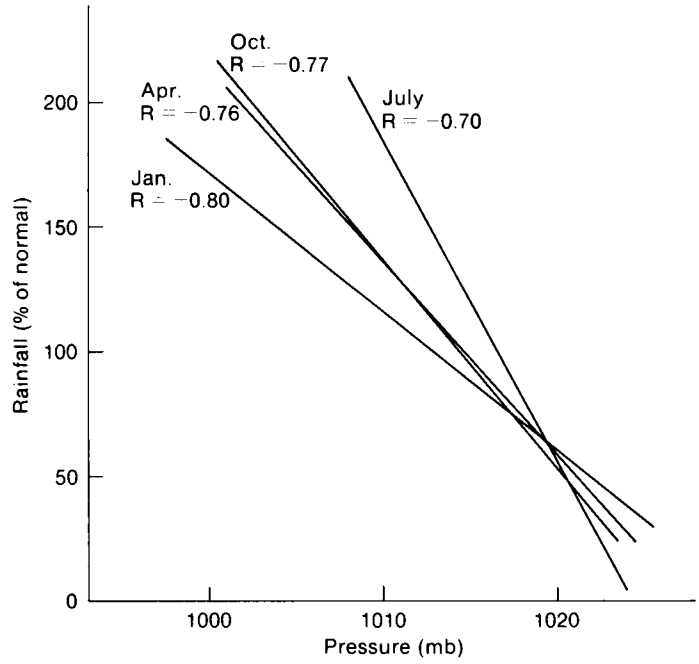
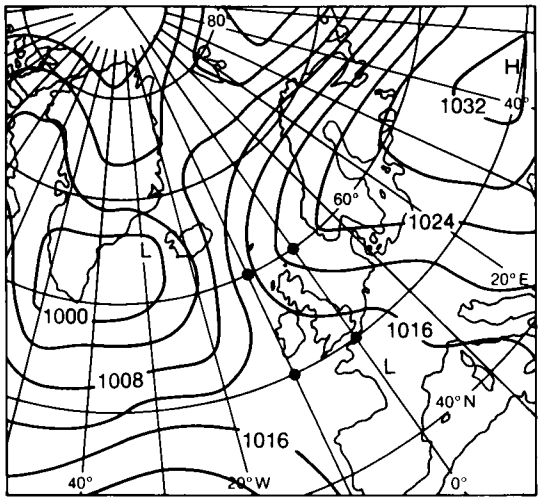


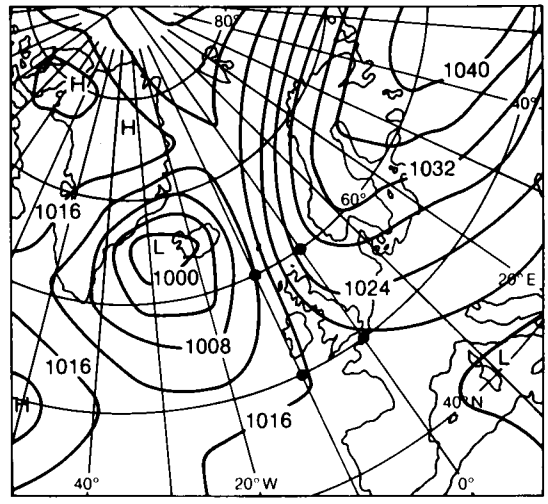
Figure 10. Selected regression relationships (R is the correlation coefficient) between mean-sea-level pressure and rainfall percentage for forecast district 8, calculated for the period 1951–85, for the first halves of the months shown.

(b) *Temperature anomaly forecasts*

The availability of numerical 1000–500 mb thickness forecasts provides a very useful foundation for medium-range predictions of temperature. The PMSL pattern matching technique that is used as a second-guess procedure for deriving the rainfall forecasts becomes the main source of the forecasts of district temperature anomalies in the middle and long ranges. Information or surmises about snow cover or, in summer, surmises about soil moisture content also play a subjective part on all three forecast time-scales. Recently, analyses of historical monthly mean SST anomalies near the UK coasts have been used to modify the temperature forecasts subjectively. The SST data are described by Minhinick and Folland (1984). Thus when using the PMSL matching technique for temperature, the difference in observed SST anomalies accompanying the historical half months chosen as best PMSL matches would be noted and also that suggested by the most recent observations (usually the most recently available pentad). A further adjustment would then be applied, if need be, to the temperature anomalies extracted from the matching historical half months. Fig. 12 shows the SST charts that were used for the mid-range forecast for 6–15 February 1986. The top two are the monthly mean SST anomaly fields (near the United Kingdom) that overlapped with the best matching PMSL fields (half-monthly SST anomaly fields are not available). However, in recent years pentad mean SST anomaly fields have been calculated and are most useful in areas like those near the United Kingdom where data is most plentiful. The SST anomaly field for 26–30 January was the most recent available to the forecasters. The SST anomalies to



Second half of Feb. 1972



Second half of Feb. 1981

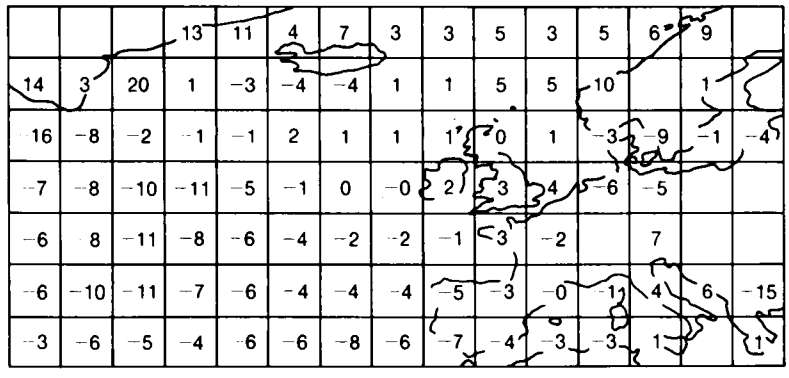
District	Temperature anomaly (°C)	Rainfall (% of average)
0	+0.2	26
1	+0.7	56
2	+0.7	53
3	+0.6	53
4	+0.6	60
5	+0.6	65
6	+0.7	45
7	+0.8	43
8	+0.4	101
9	+0.3	36

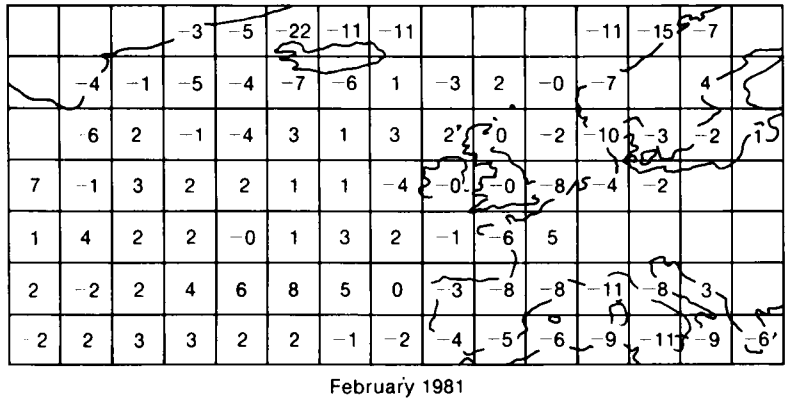
District	Temperature anomaly (°C)	Rainfall (% of average)
0	−0.8	8
1	−1.5	67
2	−2.0	85
3	−2.7	69
4	−2.8	82
5	−2.7	82
6	−2.2	41
7	−2.6	42
8	−2.3	108
9	−1.5	75

Figure 11. The two best mean-sea-level pressure (mb) matches to the forecast for 6–15 February 1986 with associated observed temperature and rainfall anomalies. (Large dots indicate the locations of the grid points used for the initial automated mean-sea-level pressure match.)

east and south-east of the United Kingdom were clearly the most important given the forecast PMSL pattern in Fig. 4. These anomalies were broadly similar to those observed for 16–28 February 1981; 16–28 February 1972 was only given a small weight as the origin of the air seemed to be further south than that indicated in Fig. 4. Allowing for the expected development of stronger negative SST anomalies over the North Sea owing to the expected blocked circulation pattern, the forecast district mean temperature anomalies derived from 16–28 February 1981 were finally given full weight. This illustrates the complex judgements that are made and the fact that the expected effect of local SST anomalies on a forecast depends on the dominant wind directions envisaged.

Variations of SST anomaly within about 1500 km of the UK coasts are quite large at most times of the year and since this technique was introduced in September 1985 there has been a noticeable impact on the quality of the hitherto poor mid-range temperature forecasts. Adjustments of 1 °C or more have quite commonly been made to district temperature forecasts initially derived from 'best PMSL matches'.





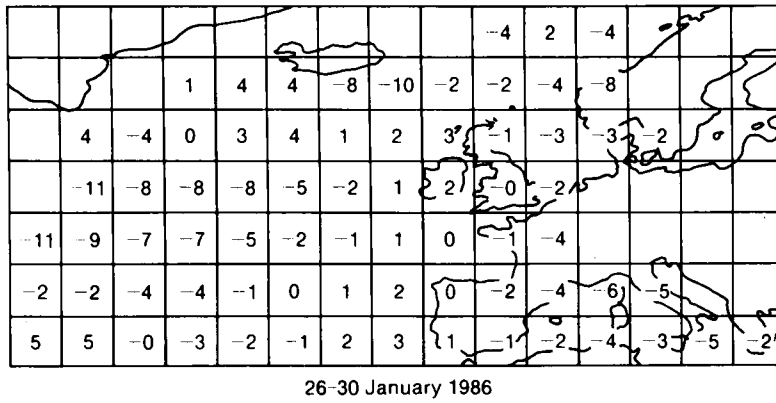


Figure 12. Sea surface temperature anomaly charts used for the mid-range forecast for 6–15 February 1986. Units are in tenths °C and are calculated from a 1951–80 average.

7. Conclusions

The long-range forecasting system is now substantially different from that used during the last few years of the public issue of the forecasts. Changes have been prominent both in forecasting techniques and in the methods of deriving forecasts of district surface weather anomalies from these techniques. The latter changes have been helped by the automatic analysis of surface climate information not previously readily available. In the near future we can expect further developments in the multivariate statistical forecasting technique and increased use of numerical long-range forecasts. A companion paper by Folland *et al.* (1986) will provide a provisional discussion of the complex impact of these changes on forecasting skill so far.

Acknowledgements

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Sea surface temperature images from Advanced Very High Resolution Radiometer (AVHRR) data

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Summary

An account is given of a pilot study to produce high-resolution polar stereographic images of sea surface temperature from Advanced Very High Resolution Radiometer data. Infra-red images at different wavelengths are combined to compensate for the attenuation of surface emission by the atmosphere, and to generate images of sea surface temperature for areas detected as cloud-free. Data from 14 overpasses of the British Isles by the NOAA-9 satellite during one week in April 1985 have been processed in this way. They have also been mapped into a polar stereographic projection and combined to give composite images for the week to illustrate how this or similar products might be provided operationally in future.

1. Introduction

Sea surface temperature (SST) data around the British Isles are currently available to forecasters in the form of a 5-day mean contour chart (Figs 1(a) and (b)) updated three times a week. These charts are produced from ship and buoy reports averaged over a 5-day period. Data from the Advanced Very High Resolution Radiometer (AVHRR) on board the TIROS-N/NOAA series of polar-orbiting satellites (Schwalb 1978) can potentially give a 5-day mean SST chart with a greatly improved spatial resolution.

The Meteorological Office plans to introduce a new computer system, AUTOSAT-2, to be used for processing digital satellite data. The availability of real-time High Resolution Picture Transmission (HRPT) data from the NOAA satellites, consisting of data from a number of instruments including

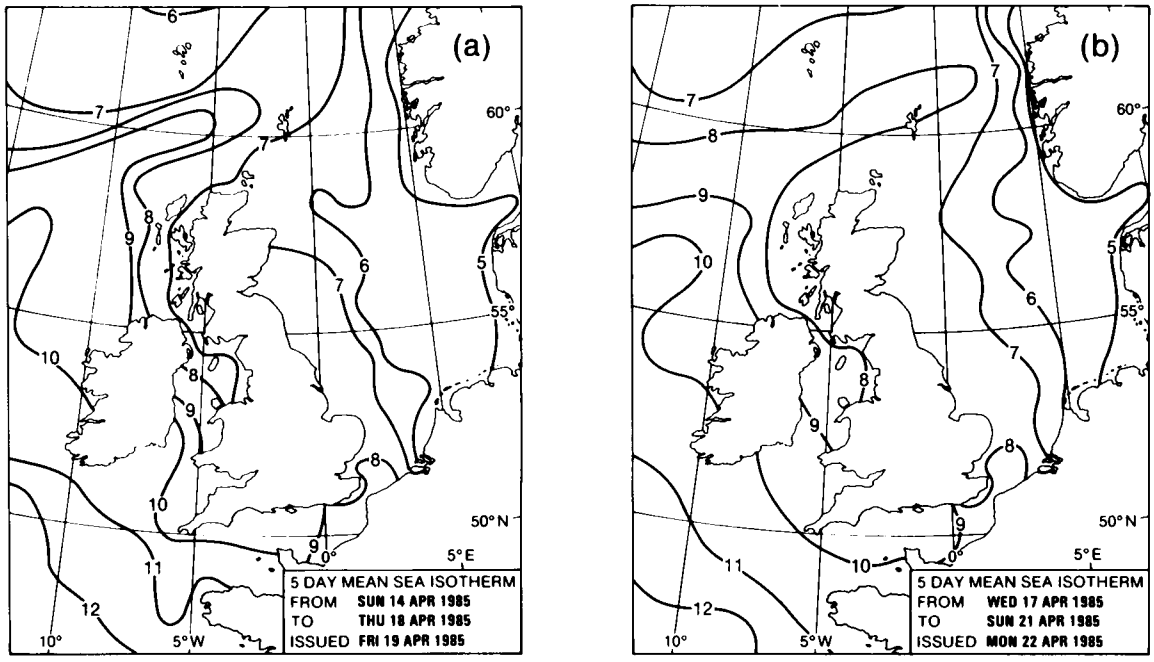

Figure 1. Conventional 5-day mean sea surface temperature (°C) charts for the seas around the British Isles for (a) 14–18 April and (b) 17–21 April 1985.

AVHRR, makes possible the generation of new operational products. The data would be received and processed at the Royal Aircraft Establishment ground station at Lasham and then transmitted to the Meteorological Office computer system at Bracknell over the METSATNET link (a new high-speed telecommunications link between Lasham and Bracknell). This paper describes an experimental scheme to produce a new SST product from the AVHRR data around the British Isles. It is intended to demonstrate how this or similar products could be derived by AUTOSAT-2.

2. Processing scheme

A general outline of the processing scheme is shown in Fig. 2 and is described in detail below. The details of the programs used on the Meteorological Office computers (HOMER and HERMES) to process the data are described by Pescod *et al.* (1986).

Reading AVHRR data

The raw input data are those received from the spacecraft as part of the HRPT data. They consist of upwelling radiance measurements made at five wavelengths (channels 1–5 centred at 0.53 μm, 0.85 μm, 3.7 μm, 10.7 μm and 11.8 μm respectively) over a field of view of about 1 km at the sub-satellite point. Each radiance is in the form of a 10-bit count, i.e. a value between 0 and 1023, but to facilitate computer processing the raw data stream is expanded from 10 to 16 bits for the channels required (1, 2, 4, and 5 for the day pass and 3, 4, and 5 for the night pass).

Computing brightness temperatures and radiances

The visible and near infra-red counts (channels 1 and 2) are converted to radiances. The infra-red counts (channels 3, 4 and 5) are converted to equivalent black body temperatures (brightness

temperatures) using the scheme outlined by Lauritson *et al.* (1979), including the non-linearity correction given by NOAA (National Oceanic and Atmospheric Administration) for channels 4 and 5.

Computing earth location

Earth location information is also computed for the image. Because of the large amount of data in an AVHRR image, it is not practicable to compute the latitude/longitude of every pixel (picture element) in the image. As a compromise, the locations of every thirty-second pixel across and along the pass are calculated. These locations are computed by first predicting the position of the spacecraft above the earth at a known time from a recent set of orbital elements (received from NOAA over the Global Telecommunication System) and then applying the satellite scan geometry to determine the locations of pixels along a scan line. The predicted position of the spacecraft above the earth is usually in error by less than 10 km but occasionally errors in the along-track direction can be more than this. To correct for this error a coastline can be computed, which is then displayed over the image. Any offsets between the

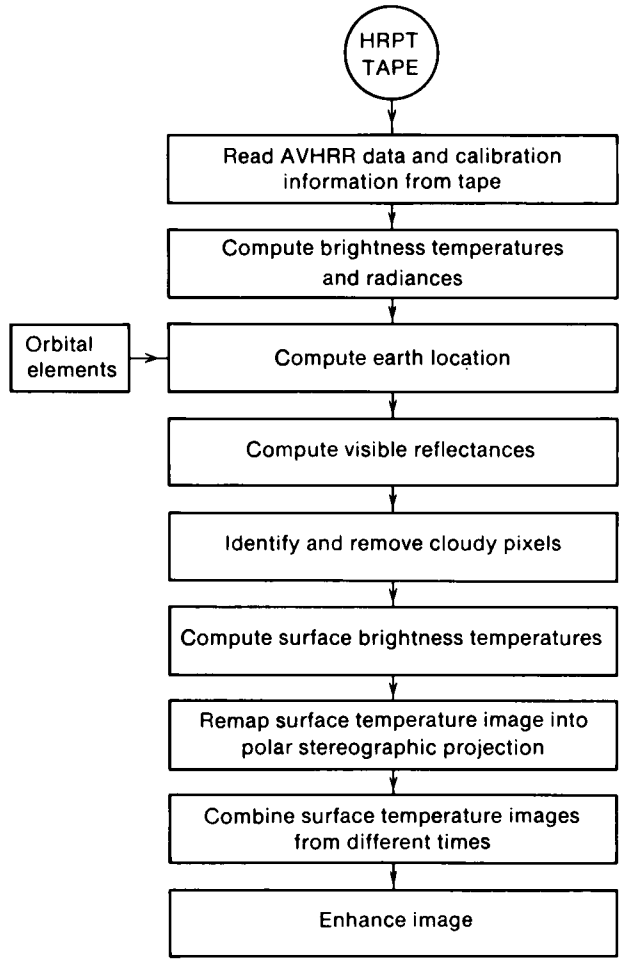
HRPT TAPE
Read AVHRR data and calibration information from tape
Compute brightness temperatures and radiances
Orbital elements
Compute earth location
Compute visible reflectances
Identify and remove cloudy pixels
Compute surface brightness temperatures
Remap surface temperature image into polar stereographic projection
Combine surface temperature images from different times
Enhance image

Figure 2. Flow diagram showing how AVHRR data taken from a High Resolution Picture Transmission (HRPT) tape is used to produce sea surface temperature images.

computed coastline and the actual coastline are then immediately obvious, and by interactively matching the two coastlines these offsets can be determined. The location information is then recomputed to include these offsets. Obviously this correction procedure is only possible when there is at least some cloud-free coast within the image. The corrected location information is used by most of the subsequent processing steps.

Computing visible reflectances

Reflectances are calculated from the visible and near infra-red channels by dividing the radiances by the incident solar radiation (at the appropriate time and location) within the filter response function of each channel. A value for the solar constant of 1365 W/m^2 is assumed (Lee *et al.* 1986) and the solar irradiance table of Neckel and Labs (1984) is used to compute the effective solar spectral radiance for each channel.

Identifying and removing cloudy pixels

The reflectances and brightness temperatures are used in a cloud detection scheme, which identifies cloud-free pixels, from which surface quantities can be derived. The scheme to detect cloud-free pixels is described in detail by Saunders (1986). Each pixel must pass five independent checks for cloud contamination. Different tests are applied according to whether it is day or night and on the type of underlying surface, i.e. sea, land or coast. The pixels which pass all of these tests are then assumed to be cloud-free.

Computing surface brightness temperatures

The cloud-free infra-red brightness temperatures are then converted to SSTs using the relationship described by Llewellyn-Jones *et al.* (1984) to remove atmospheric effects. This relationship takes the form of a linear combination of the 10.7 and 11.8 μm channels as follows:

$$SST = C_0 + C_1T_4 + C_2T_5$$

where SST is in Kelvin, and T_4 and T_5 are the brightness temperatures in channels 4 and 5. The regression coefficients C_0, C_1 and C_2 vary with 'air mass', i.e. secant of the satellite zenith angle. Values of SST are only computed for satellite zenith angles less than 60°, so that data at the edge of the scan lines (less than 100 pixels from the edge) are not used.

Remapping surface temperature image

The SST image of the earth as viewed by the AVHRR instrument is now remapped on to a polar stereographic projection plane (at 60° latitude). This projection was chosen to be compatible with the current operational charts. The details of the projection process are given by Pescod *et al.* (1986). The display device which has been used is a SIGMEX Advanced Raster Graphic System (ARGS) with a resolution of 1024 × 1024 elements. With this in mind the map area and scale of projection (in km/pixel) on the screen are chosen. In this experiment a final product was created for an area in polar stereographic projection bounded by latitudes 47° and 60° N and longitudes 12° W and 10° E, i.e. about 1400 × 1400 km. To select from one image all the pixels which may fall in this area, it is necessary to consider a swath of about 1600 pixels wide from the full AVHRR image.

The location of every thirty-second line and pixel is achieved as described above. The locations of all other pixels are then fixed by two-dimensional linear interpolation. The reprojection process allows a number of input images from different parts of a pass to be reprojected on to the same polar

stereographic plane. With this simple scheme, it was sometimes found that more than one input pixel mapped to a single pixel in the output image and in these cases the pixel corresponding to the maximum surface temperature was the one used. Conversely, it was found that towards the edges of an AVHRR data swath, pixels in the reprojected image remained unfilled. This problem was overcome by assigning a pixel in the input image to as many as 9 pixels (as necessary) in the output image, for pixel positions in the input image greater than 824 pixels from the sub-orbital track.

Combining surface temperature images from different times

The next step merges the reprojected data from different passes on several days (seven in this case) into one composite SST image. The procedure chosen (from several possibilities) was to retain the maximum SST value encountered for each pixel in the output image during the seven days. This helped to remove spurious low temperatures due to any remaining undetected cloud contamination. This does have the disadvantage that if a strong diurnal thermocline is present, significant diurnal variations in SST can occur and go unrecorded, e.g. as seen by Saunders *et al.* (1982). This would bias the composite image to the warmest values and not give a true mean. With the advent of improved cloud detection algorithms, this limitation could be removed and a true mean SST value computed. A better method of detection and removal of spurious pixel values (for whatever reason) could also be devised if a background field was available.

Enhancing the image

To reduce the noise in the final image a median filter can be applied. This causes some reduction in the resolution of the product but is acceptable because of the low horizontal variability of SST. After combining seven days of data, it was found that the final image contained areas which had been cloud contaminated on all 14 passes. This resulted in some data voids. Voids of a few pixels were effectively removed by the median filter.

3. Results

The HRPT data used in this study were obtained on computer-compatible magnetic tapes from the University of Dundee. They consisted of one daytime and one night-time NOAA-9 pass over the British Isles during the week 14–20 April 1985, which corresponded to overpass times of approximately 0300 and 1330 GMT. The data used in this experiment were not a carefully selected set of cloud-free data, but seven days of contiguous data during which typical cloud cover was experienced.

The composite SST image produced by the processing scheme described above is shown in Fig. 3. For comparison two conventional 5-day mean SST charts for the same period, which were used operationally, are shown in Figs 1(a) and (b). These represent the bulk water temperature to a depth of about 1 m.

Comparing the conventional charts with the satellite product it can be seen that there is general agreement in temperature values between them, and that the major features are discernible in both. One such feature is the tongue of warmer water off north-west Scotland and Ireland. Another is the cold coastal strip of water off the Norwegian west coast as studied by Mork (1981). However, there is far more detail in the satellite plot than can be inferred from the conventional charts. For instance, the precise structure of the feature to the West of Scotland or the strong temperature gradients between the Irish Sea and the sea areas between Cornwall and south-eastern Ireland. A warmer (greater than 7 °C) patch of water on the Dogger Bank in the North Sea is also evident in the satellite data. One or two of the features, however, may still be artefacts caused by incomplete cloud clearing such as the plume of warm water reaching into the North Sea from the Dutch–German border. Fig. 4 shows the day/night

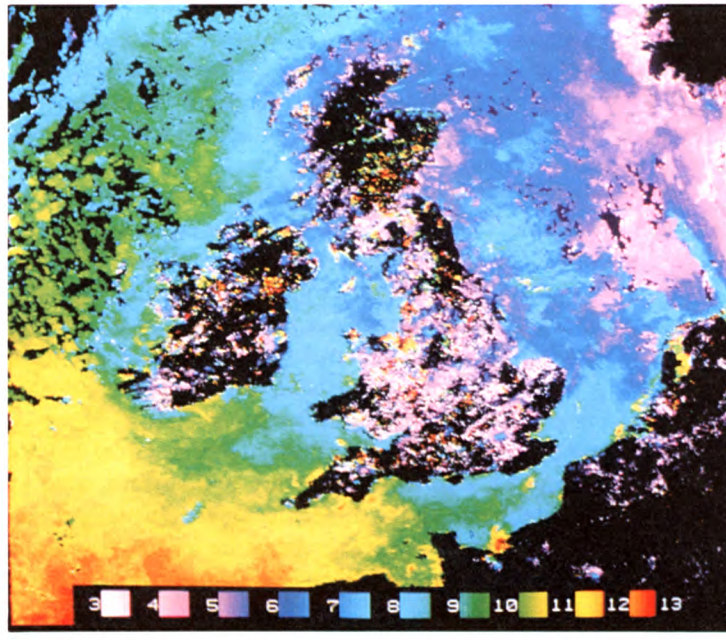

Figure 3. Composite sea surface temperature image which combines cloud-free AVHRR data from seven daytime and seven night-time passes for 14–20 April 1985. Over the sea, black areas remained cloud covered during all fourteen passes. Over the land, temperatures were mostly outside the range of the colour table and hence also appear black. The scale shows temperatures in °C.

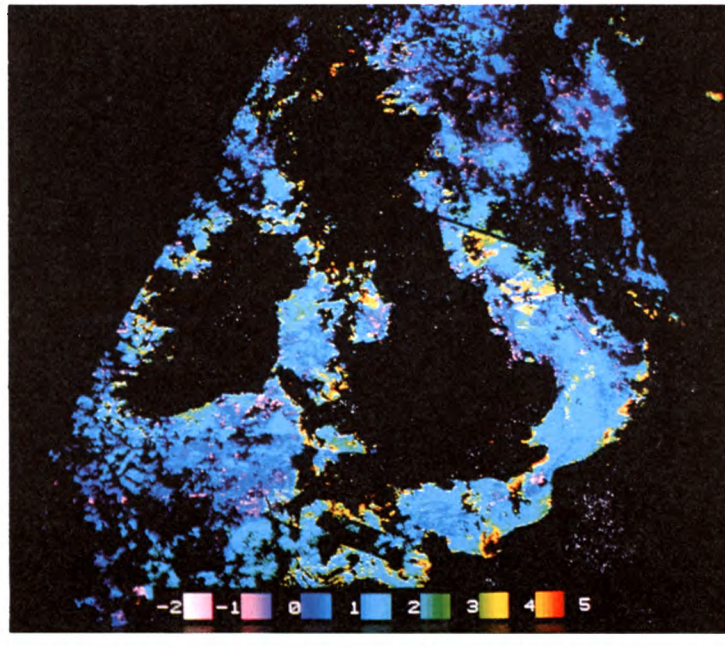

Figure 4. Day–night temperature difference image computed from AVHRR data for the period 14–20 April 1985. The scale shows temperature differences in °C.

temperature difference image for the seven days of data. In general the SST differences are close to zero but near to the coasts the daytime values are up to 4 °C warmer than the corresponding night-time values which would be expected over shallow coastal waters. The absence of large positive temperature differences over the open sea is evidence that a diurnal thermocline was not present during these 7 days. The small number of negative differences (i.e. where the night-time SST value is greater than the daytime value) is probably due to inadequate cloud clearing.

The absolute satellite SST values are in qualitative agreement with the conventional charts. A more comprehensive comparison of satellite SSTs, computed using the equation above, and ship SSTs was carried out by Llewellyn-Jones *et al.* (1984) and showed that the root-mean-square difference between the two was 0.53 °C with a bias of −0.10 °C. The satellite measures a surface skin temperature so the two measurements will only agree if the skin temperature is representative of the underlying bulk water temperature. There are two effects which can produce a significant difference between the bulk water temperature and the skin temperature. The first is the 'skin effect' which causes the skin temperature normally to be a few tenths of a degree colder than the bulk temperature, as observed by Robinson *et al.* (1984). The second effect is caused by the formation of a diurnal thermocline, which occurs when the top layers of the ocean are not well mixed, e.g. when there are low surface wind speeds. Under these conditions the incident solar radiation heats up the uppermost layers (usually a few tens of centimetres thick) of the sea surface. This results in a surface skin temperature up to a few degrees warmer than the bulk water temperature during the early afternoon which is the time of the NOAA-9 daytime overpass.

4. Conclusions

An SST image was produced from data from 14 passes of NOAA-9 during the period 14–20 April 1985. However, even over this 7-day period some pixels in the output image were cloud contaminated for every pass. More NOAA-9 passes per day could be processed rather than just the two used here, which would improve the extent and density of coverage a little. When the second NOAA polar-orbiter satellite is operational then data from this satellite may help reduce the number of cloud-contaminated areas. Compared with conventional charts, the satellite product gives good agreement in absolute SST values but shows far more detail. It is questionable whether most forecasting applications need such a high-resolution product, but for upgrading the conventional chart by filling in data void areas where there are no ship reports this product would undoubtedly be useful. In addition, this new satellite product would be useful for such applications as deriving a local high-resolution SST climatology and the location of ocean fronts (for fisheries and other applications). Although this scheme was designed for use over the sea it has been used with some success over land though differences between land and sea, such as surface emissivity and atmospheric profile structure, lead to larger uncertainties. It is therefore possible to obtain high-resolution land surface temperatures from these data. However, the interpretation of composite products is complicated — different areas contribute to the composite on different days, and the product is biased because it applies only to cloud-free cases. Nevertheless, surface temperature is just one example of a product which may be derived from AVHRR data; high-resolution climatologies of cloud cover, snow cover, surface albedo and other parameters could also be generated using a similar approach.

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An account of the International Conference on Polar Lows, Oslo, 21–23 May 1986

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1. Introduction

The recent extension of offshore operations to high latitudes, especially off the coast of Norway, has led to increased interest in weather conditions in these areas. Much of the interest has been directed towards polar lows which form close to the edge of the Arctic ice sheet and move southwards with associated severe weather (gale force winds and snow) and high waves. Owing to their small size (a few hundred kilometres in diameter), and their rapid movement and development in regions of sparse observations, it is difficult to forecast polar low evolution with the accuracy necessary for offshore operations.

A three-year project was recently undertaken, on behalf of a consortium of operators with licences for operations north of 62° N, by several groups including the Norwegian Meteorological Institute (DNMI) and the Oceanographic Company of Norway (Oceanor). Support for field projects was also provided by groups outside Norway including the National Oceanic and Atmospheric Administration (NOAA) and the Meteorological Office. The subjects included in the project were the climatology of polar lows, case studies, dynamical theories, numerical modelling, observing systems, forecasting, and ocean waves associated with polar lows.

To mark the completion of the project the International Conference on Polar Lows was held near Oslo to bring together experts, not confined to participants in the project, to assess the current state of knowledge. The conference was opened by Arne Grammeltvedt and Magne Lystad of DNMI who outlined the main findings of the project, especially the climatological aspects and the range of techniques used to forecast polar lows. It was shown that although 20–30 polar lows with observed

winds up to 35 m s^{-1} are experienced each year in the area between Norway and Spitzbergen, they do not present the most stringent design problems. However, forecasting and operational problems are posed by the rapid movement of polar lows and the notice required to stop certain crucial operations.

After the introductory session, the conference followed the general areas of interest included within the Norwegian polar-low project.

2. Climatological studies

A range of detailed climatological studies was presented. Erik Rasmussen (University of Copenhagen) described five archetypes of polar lows including some with the appearance of lee vortices and others which appeared more baroclinic, e.g. when the low-level thermal wind opposed the surface northerly flow. It was suggested that the deepening occurred in three distinct phases with rapid deepening following initial triggering by baroclinic instability. Kari Wilhelmsen (DNMI), in an analysis of 76 Norwegian Sea polar lows, showed that although the peak period for their formation was in winter and spring there was a pronounced minimum in February, probably due to the general circulation being influenced by very cold land surface temperatures and a displacement of the main baroclinic zone. In general, the atmosphere above 800 mb was relatively dry, and warming was associated with both surface exchanges and differential advection. In contrast to this Norwegian Sea analysis, Steve Businger (University of Washington) presented results from the Gulf of Alaska where there is no February minimum in the frequency distribution. His analysis suggested that polar-low outbreaks lasting several days sometimes occurred. Polar lows were associated with cold anomalies at 500 mb (6 K deficit) and formation was often associated with the movement of the cold anomaly over warm sea surfaces.

Ingolf Kanestrøm (University of Oslo) described some promising attempts to identify conditions favourable to polar low development based on pressure differences between certain key locations and the presence of anomalies at 500 mb. Michael Bilello (US Army Research Laboratory) then presented results from a survey of surface lows that identified key areas for formation and signatures of rapid deepening and which also appeared to have some predictive capability.

3. Case studies

Detailed case studies of rapidly deepening lows were presented by Fred Saunders (Massachusetts) and by Mel Shapiro (NOAA, Boulder). The former presented a composite study of rapid cyclogenesis off the east coast of the USA making use of synoptic data. It was shown that rapid deepening was associated with the region of maximum sea surface temperature gradient on the cold side of the Gulf Stream. At the time of rapid deepening, the region of maximum upper-level vorticity advection was about 300 km behind the surface centre. Upper-level vorticity advection, rather than the position of the vorticity maximum, appeared to provide the best discriminator between explosive and less rapidly deepening systems. Similar patterns were also associated with a rapidly deepening low over Lake Superior when a long-wavelength upper trough coincided with a small surface feature over the warm water. Shapiro presented the results of an analysis of aircraft data obtained in a polar low north-east of Iceland on 27 February 1984; this remains the only case where detailed aircraft observations have been obtained in a polar low. The data show a warm core structure, two strong shear lines, an intensity which decreases with height, and maximum winds close to the surface with gusts to 40 m s^{-1}. Analysis suggested that the air was unstable to ascent along absolute momentum surfaces and that the surface sensible heat flux of 500 W/m^2 was comparable with the latent heat flux. Total Ozone Mapping Spectrometer (TOMS) data suggested that the tropopause descended to low levels in this system.

Other case studies were presented by Åsmund Rabbe (DNMI) who presented an analysis based on synoptic data of a polar low which developed two days later than that reported by Shapiro and which formed part of a 'system' of developing polar lows, and by Businger who described a Gulf of Alaska

storm. Both of these case studies exhibited features similar to the case on 27 February with evidence of important baroclinic processes.

A paper in this session by Peter Aakjaer (Danish Meteorological Institute (DMI)) included results from a grid-point model reproducing an observed case but using simplified atmospheric profiles. It was shown that adequate surface fluxes were crucial to obtaining realistic simulations and that boundary-layer convergence was a major source of moisture in this example. R.A. Brown (University of Washington) showed how the atmospheric boundary-layer structure changed when moving downwind from the ice edge.

Use of satellites for the study of polar lows was described by Michael Steffensen (University of Copenhagen) who demonstrated the importance of using radiosonde data in deriving profiles by regression techniques, and by Anke Thoss (Free University of Berlin) who outlined the problems associated with wind retrieval from Meteosat cloud images, but suggested that useful data could be obtained at medium or high levels even at 70° N.

4. Dynamical theories and modelling

Dynamical ideas and numercial modelling were treated together in the third session. Dick Reed (European Centre for Medium Range Weather Forecasts) presented several results which suggested that baroclinic instability was the major mechanism for rapid deepening with upper-level vorticity maxima but limited surface heating. However, other examples were much shallower with greater surface fluxes, but these were also often associated with strong local baroclinicity. Hans Økland (University of Oslo), however, described a CISK (Convective Instability of the Second Kind) model with time and space dependent heating. Analysis showed that growth rates of instabilities were modest for a 500 mb deep model, but increased when heating was confined below 800 mb. It was considered that CISK may develop within a larger scale baroclinic system and some observations, e.g. pressure traces, supported the suggestion of a 'two scale' structure for polar lows.

The model presented by Kerry Emanuel (Massachusetts Institute of Technology) suggested that forced ascent of warm moist boundary-layer air, even though soundings were stable, could release energy to spin up a polar low, with the necessary ascent forced by larger-scale baroclinic instability. The model (an air–sea interaction model) was thermodynamically consistent and an axisymmetric numerical model suggested that it was dynamically possible to produce rapid cyclogenesis in this manner.

Numerical simulations of polar lows were presented by Erik Haugen (DMI) who undertook sensitivity studies with idealized flows demonstrating the importance of the initial horizontal scale of the disturbance, and by Sigbjørn Grønas (DNMI) who showed that a forecast model with 25 km resolution could predict the occurrence of polar lows up to 48 hours ahead but tended to over-predict the occurrence and underestimate the depth. Thor Nordeng (DNMI) showed that the inclusion of a parametrization of slantwise convection could in some cases improve the simulation of the depths of polar lows, while T.S. Pedersen showed that conversion of thermal to kinetic energy was most efficient about 3 km above the surface and that the efficiency was increased if the heating was concentrated in space.

5. Polar-low forecasting

Forecasting of polar lows requires adequate data and this was discussed by L. Fedor (NOAA, Boulder) who showed methods of improving the presentation of satellite data to improve the early identification of polar lows, and Grammeltvedt who described the current observation network in the Norwegian coastal areas including buoys, the use of satellite data and the possible future use of a network of three radars covering the area between the Norwegian coast and Björnöya (south of Spitzbergen). Peter Jonas (Meteorological Office) took up the latter point and showed how radar data

could be used to derive the movement of intense mesoscale features and, by tracking shallow precipitating convective cells, to estimate peak gusts in exposed locations. Methods of identifying conditions likely to lead to polar-low formation were discussed by Knut Midtbø (DNMI) who obtained good results by applying statistically-derived criteria to numerical forecast charts.

Lars Eide (Norsk Hydro) identified the critical problems concerning offshore drilling operations, pointing out that for such operations the necessary lead time required to restore rigs to a stable state where they are insensitive to high winds could be as much as 5 hours. Most operations could be undertaken at wind speeds up to force 8 but above this speed some operations were impossible. Christian Zick (Free University of Berlin) and Per Gloersen (National Aeronautics and Space Administration, Greenbelt) showed films of satellite data which demonstrated respectively the detailed development and decay of two polar lows, and the strong seasonal dependence of disturbed conditions together with the rapid variations in ice cover.

6. Polar lows and ocean waves

The final session was devoted to discussion of the effects of polar lows on sea state. Duncan Ross (University of Miami) showed that directional wave spectra associated with the passage of polar lows differed from model predictions when the storms were moving rapidly. It was often necessary to use models with a grid of 10 km or less to obtain realistic spectra. In many examples, focusing and defraction of the waves by currents or topography, especially near coasts, had a significant effect on the wave spectra. Alf Harbitz (University of Tromsø) showed how resonance between the movement of waves of certain wavelengths could give large waves over a narrow band of wavelengths despite the apparently short fetch (much less than the 1000 km or so normally required to reach maximum amplitude). These ideas were also supported by laboratory experiments reported by Torkild Carstens (Norwegian Hydrotechnical Laboratory).

Ken Davidson (US Navy Postgraduate School) described plans for the next Marginal Ice Zone EXperiments (MIZEX) in early spring 1987. While the programme was largely oceanographic, making use of remote-sensing techniques to examine sea state and ice cover, an extensive meteorological programme was also envisaged to characterize the relationships between surface fluxes and cyclogenesis, and the relationships between mesoscale meteorological features and the surface state. At present the meteorological programme was hampered by the lack of upper-air observations which could, perhaps, be provided by dropsondes.

Dag Gjessing (Norwegian Environmental Surveillance Programme) showed how new radar signal processing techniques could be used to obtain wave spectra related to specific types of forcing, while Ole Houmb (Oceanor) showed how the waves produced by polar lows were often of higher frequency than those associated with other depressions, but that the maximum significant wave heights were generally lower than those from other storms owing to the limited fetch.

7. Summary

The meeting demonstrated that considerable progress is being made towards improving polar-low forecasting but that numerical forecasts of polar lows are often not sufficiently accurate or unambiguous to provide adequate warning for offshore operators. New sources of data appear to offer some chance for improved forecasts particularly when used subjectively, but the basic mechanism for the rapid development remains uncertain although it is probably a combination of causes which may differ in relative importance between different examples.

The meeting was very successful in bringing together 66 scientists with a range of backgrounds (forecasters, theoretical meteorologists, observationalists and oceanographers) and, by concentrating on a specific topic, discussion was both uninhibited and constructive. Definitions of polar lows were

almost as numerous as the participants and it is probably true that the term includes a range of systems with different mechanisms. Basic research is still hampered by the limited observations of polar lows formed under different conditions, and further detailed observations are essential if the basic mechanisms are to be clarified and reliable forecasts produced.

551.551.5

Prolonged clear air turbulence over the British Isles on 4 September 1985

By L.A. Hisscott

(Meteorological Office, Ronaldsway Airport, Isle of Man)

Summary

Clear air turbulence (CAT) is normally a transient and localized phenomenon. An unusual outbreak of moderate to occasionally severe CAT, which covered a large area and persisted for several hours, is described. The occurrence was associated with diffluence and anticyclonic turning below a warm frontal zone.

Clear air turbulence (CAT) is important to aviation from the point of view of both safety and passenger comfort. Usually it is localized in space and short-lived in time. However, extensive and prolonged CAT occurred over the British Isles on 4 September 1985. The existence of this phenomenon over a large area and its persistence for several hours are extremely rare.

Manx Airlines flight 303 departed from Ronaldsway at 0740 GMT, and arrived at London/Heathrow about 0900 GMT. The same Viscount aircraft and crew returned as flight 304 to arrive back at Ronaldsway at 1100 GMT. The captain, with many years of military and commercial flying experience, returned to the meteorological office to report that they had encountered moderate, occasionally severe, turbulence continuously on both legs of the trip, and that it was the roughest flight he had ever experienced. The outward leg was operated at a flight level of 14 000 ft (FL140) and the return leg at FL100, both in clear air just below thick layer cloud.

Fig. 1 shows the surface synoptic situation at 0600 GMT on 4 September 1985, with a ridge over the British Isles ahead of a depression west of Ireland, and a warm front just advancing into south-west Ireland. The air mass over the south of the British Isles gave broken stratus and stratocumulus cloud layers, the base generally at about 1000 ft (but 200–400 ft on windward coasts) and the top at about 5000 ft, and thick layer cloud, associated with the overrunning warm air, above 14 000 ft, which lowered as the warm front approached. Fig. 2 shows winds at 14 000 ft and 10 000 ft reported at 0600 GMT by upper-air stations in the British Isles and near continent. The 700 mb contours have also been drawn, by interpolating between the 0000 and 1200 GMT data.

The area in which CAT was reported can be associated with deceleration and anticyclonic turning of the west-south-westerly airstream, factors often relevant to the occurrence of CAT. In fact there was a ridge pattern in the contours at all levels over the British Isles at the time, with a SIGMET* of severe

* A SIGMET is an in-flight warning of certain significant weather phenomena.

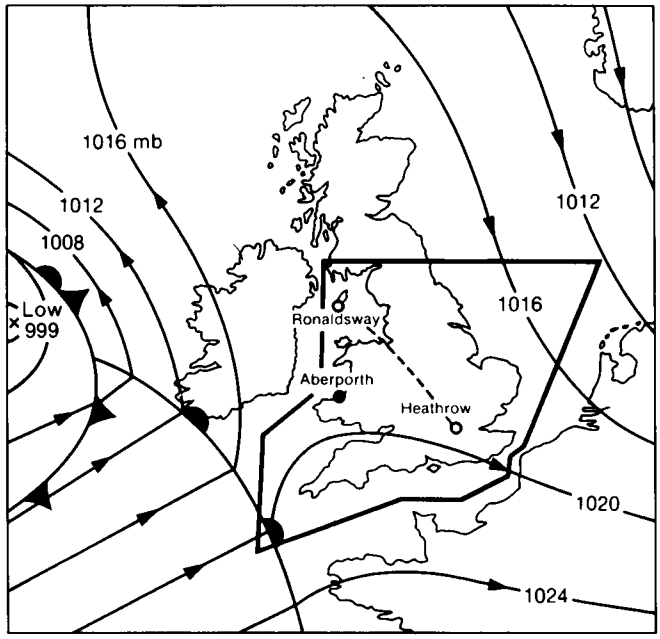

Figure 1. Surface analysis at 0600 GMT on 4 September 1985 showing route of Ronaldsway-Heathrow-Ronaldsway flight. The bold lines show the area covered by the London Flight Information Region.

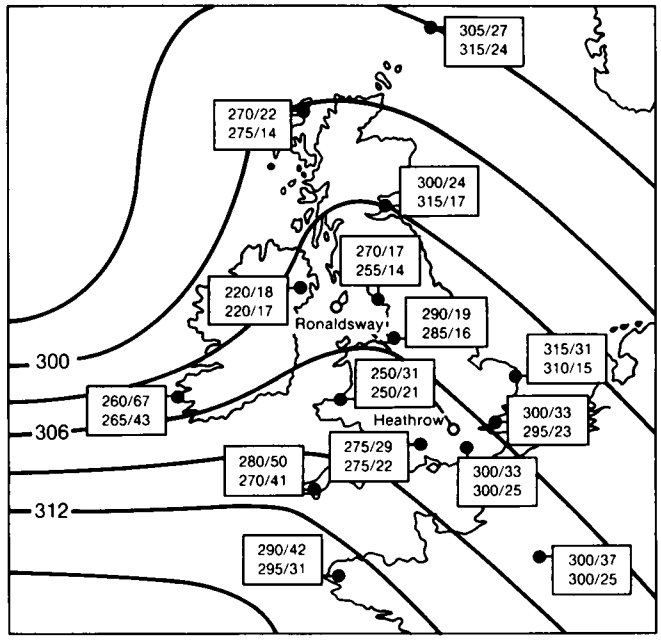

Figure 2. Interpolated 700 mb contour chart at 0600 GMT on 4 September 1985. Dots indicate upper-air stations and connected boxes contain 0600 GMT winds at 14 000 ft (upper figure) and 10 000 ft (lower figure). Contours are in decageopotential metres and wind speeds are in knots.

CAT between FL180 and FL420 in operation for the London Flight Information Region (see Fig. 1). However, the unusual feature of this case is that the reported extensive turbulence occurred below the frontal zone within the weak upper ridge. The dry unstable layer below the warm frontal zone, shown by the almost dry-adiabatic environmental lapse rate between 700 and 615 mb on the Aberporth ascent (Fig. 3), indicates strong mixing in this layer due to the severity and longevity of the turbulence. However, the continuous production of this intensity of turbulence over such a long period must be due to the broader-scale dynamics of the situation. There is a region of marked diffluence ahead of the 700 mb trough at 0600 GMT (Fig. 2) that moved east-north-east. The associated ascent of the air applied to the Aberporth sounding could presumably have maintained and deepened the instability for the return flight, but it is still difficult to understand why the moderate to occasionally severe CAT lasted so long.

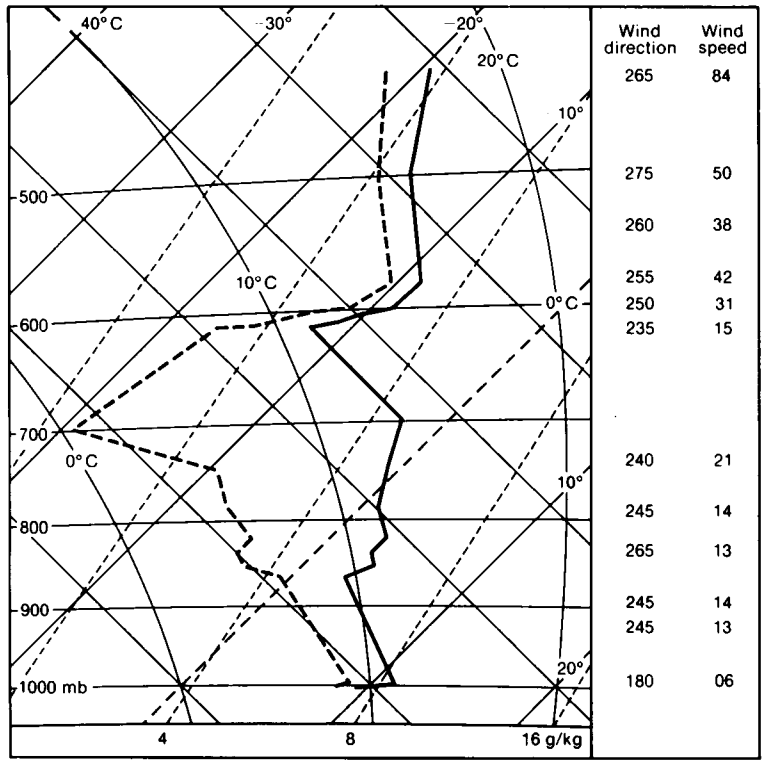

Figure 3. Aberporth radiosonde ascent at 0600 GMT on 4 September 1985 (wind speeds in knots).

Acknowledgements

I would like to thank Captain R. Coker of Manx Airlines for reporting this incident, the Senior Forecaster at Ronaldsway for permission to publish the data, and Mr M. Dutton of the Central Forecasting Office at Bracknell for his useful comments.

Notes and news

Workshops about the middle atmosphere

Two workshops entitled 'Middle atmosphere of the southern hemisphere' and 'Gravity waves and turbulence in the middle atmosphere' will be held consecutively at the University of Adelaide between 18 and 22 May 1987. Each workshop will contain invited reviews and contributed papers. Among the topics to be covered are:

Middle atmosphere of the southern hemisphere —

- Inter-hemispheric differences
- Intercomparison of observations and analysis
- Climatology and seasonal evolution
- Large-scale waves and wave–mean flow interactions; sudden warmings and final warmings
- Coupling of troposphere and middle atmosphere
- Dynamics of equatorial regions and inter-hemispheric coupling
- Transport of middle atmosphere constituents
- Numerical modelling

Convenor: Dr A. O'Neill (Meteorological Office, United Kingdom)

Gravity waves and turbulence in the middle atmosphere —

- Theory, modelling and parametrization
- Climatologies of gravity waves and turbulence
- Spectral studies; observational and theoretical interpretations
- Sources, propagation and saturation
- Gravity wave and turbulence variability; mechanisms
- Observational and data-processing techniques

Convenor: Dr D.C. Fritts (University of Alaska, USA)

Further information is available from the convenors or from Dr R.A. Vincent, Physics Department, University of Adelaide, PO Box 498, Adelaide 5001, Australia.

Advisory group on greenhouse gases

Radiatively active constituents in the atmosphere, including aerosols, which tend to increase the temperature of the lower atmosphere are sometimes referred to as greenhouse gases. In recent years there has been increasing interest in the assessment of the role of these gases, particularly carbon dioxide (CO_2), in climatic variations. This interest has led to the establishment of an Advisory Group on Greenhouse Gases (AGGG) by the International Council of Scientific Unions, the United Nations Environment Program and the World Meteorological Organization.

At its first meeting in Geneva on 1–2 July 1986, the AGGG strongly supported the statement from the 1985 Villach Conference on the 'Assessment of the Role of Carbon Dioxide and other Greenhouse Gases in Climatic Variation and Associated Impacts' that the effects of increases in CO_2 and other trace gases that cause the greenhouse effect (such as methane, chlorofluorocarbons (CFCs) and oxides of nitrogen) could produce an increase in global mean temperature of between 1.5 and 4.5 °C in the first half of the next century; the corresponding rise of sea level might reach between 20 and 140 centimetres.

The AGGG stressed the need to improve the basic understanding of the climate system and its response to both natural and man-made forcing mechanisms. Since the ozone depletion problem and the greenhouse gas problem are interlinked through the impact of the same chemicals, the Group urged

that the study of these two problems be combined. They also suggested that there are two preventive measures that should be considered to alleviate the problem:

(i) The introduction of energy conservation schemes especially those that increase the efficiency of energy use.

(ii) Substitution for CFCs in a number of uses for which alternatives are available.

Formation of an Association of European Climatologists

For a number of years British and Greek climatologists have arranged joint scientific meetings. At the last such meeting in Athens climatologists of both countries agreed to try to set up an Association of European Climatologists. The aim of the association is to foster the study of pure and applied climatology within the whole of Europe, and to promote collaboration between European climatologists. Full membership of the association is open to professional climatologists and those working in allied and associated professions; associate membership is available to amateur climatologists. Further information about the association is available from Dr A.H. Perry, Department of Geography, University College, Swansea, Wales.

Reviews

Fields, currents and aerosols in the lower troposphere, by R. Reiter. 150 mm × 240 mm, pp. xix + 714, *illus*. A.A. Balkema, Rotterdam, 1986. Price £29.75.

This well-produced book by Reinhold Reiter represents an extensive report of an observational programme at a network of mountain stations in the Bavarian Alps (particularly the Zugspitze massif). The work mainly spans the years 1950–61 and involves measurements of atmospheric electricity, aerosol concentration and radioactivity, both natural and artificial (man-made), together with more conventional meteorological observations. The book is No. 71 in the Natural Sciences Series, a collection of scientific research reports originally published in German in 1964, and published in English for the first time over 15 years later.

The material is weighty, both literally (714 pages and 1.25 kg) and in its scientific content. As the author admits, he had to drop the idea of including all the latest literature when producing the English version in order to preserve the original character of the book as a specific report of ten years of research. This is reflected in the references, about 50% of which were published between 1950 and 1960. Indeed, the recent references, that is post-1970, refer almost exclusively to the results of the Bavarian observational programme in the 1950s, and a significant portion of these are attributed to the author. Hence, one must not approach this text expecting to find a balanced 'state of the art' review, although there are many references to work from 20 or more years before the observational programme which provide a sound historical perspective.

The treatise begins with a justification for making measurements at fixed mountain stations as opposed to those made using probes in the free atmosphere. This section eventually comes to the correct conclusion, that the techniques are complementary, but frustrates the reader with its needlessly tedious argument. The relationship between atmospheric electricity and radioactivity is stated, and the order in which topics are to be discussed is justified. There follows an excellent review of the environment and nature of the observing stations and the measurement techniques employed, including the interesting use of what is termed a 'movement diagram', constructed by plotting measurements from a valley station against those made at a mountain station.

The diurnal and seasonal variations of the electric field and radioactivity of different elements, the relationships observed between wind speed and direction, humidity, precipitation and aerosol concentrations and electrical field and radioactivity, are all unfolded from the observations. At times the reviewer felt almost overwhelmed by facts and figures as each page was turned. Nevertheless, the standard of translation is high, although there are occasionally rather strange statements (for example, on page 23: 'It is known that the local climatic factors influence the relationship between atmospheric electricity and radioactivity more or less strongly, and . . .'), and there are few typographical errors, all of which makes the text easy to read. The main criticism is that one does not know quite what to expect from page to page; theory interrupts observations, special observations from short field projects precede or follow long-period observations.

The section on radioactivity convincingly explains observed variations in terms of the following: variations of weather type — convective or frontal; meteorological parameters, particularly wind direction from areas of naturally occurring radioactivity in Alpine rocks; and the occurrence of known atomic explosions during the period, in the Sahara and elsewhere. Some tantalizing suggestions are made regarding the speed of transport of nuclear-fission products between the mountain top and the valley bottoms, and the presence of such material on glaciers, in grass and in animal organs, all of which is particularly topical in the wake of the recent Chernobyl disaster.

The author is certainly not understating his findings when he concludes by saying 'We find a mosaic of individual facts and observations before us.' There is much in this book to interest, indeed stimulate, those concerned with atmospheric electricity and radioactivity. The reader should be aware, however, that the observations often prompt further questions. This is a book that most meteorologists will find very interesting, and some will find in it invaluable source material to be confirmed or challenged. It may be, as the publishers suggest, that this book will become recognized as a major reference work.

C.G. Collier

Weather at sea, by D.M. Houghton, 180 mm × 240 mm, pp. 64, *illus*. Fernhurst Books, Steyning, 1986. Price £5.50.

This book has been written in consultation with the Royal Yachting Association (RYA), and is therefore likely to be used as a supporting text for the meteorological component in RYA certificate courses in sailing and navigation. The book assumes no knowledge of meteorology, but does appropriately assume some knowledge of sailing and navigation. It is directed at yachtsmen who are likely to do most of their sailing in coastal waters, the emphasis being mainly on coastal weather typical of the British Isles. Some of the book's content can also be found in another recent book by D.M. Houghton (*Wind strategy*, Fernhurst Books, Steyning), but is here presented in a slightly more condensed and simplified form.

Early sections of the book deal mainly with weather basics, comprising short chapters covering the general circulation, pressure/wind relationships, stability and air mass concepts, clouds, and middle-latitude weather systems. In parts, the presentation is either too precise or too incomplete to make much sense, as in the opening section on global wind systems where the text does not actually explain the accompanying diagram depicting south-westerlies at our latitude; whilst elsewhere there are a few inconsistencies and odd usages which are likely to confuse some readers. The author's choice of the term 'pressure-gradient wind' (later 'gradient wind') in place of 'geostrophic wind' is questionable; not so much on semantic grounds as on the grounds that yachtsmen are likely to come across the more conventional term elsewhere without necessarily being aware that it is synonymous.

Following a well-presented section on clouds and how they can be used to identify weather type, the author introduces some of the terminology of synoptic weather systems, ending with an observation to

the effect that fronts are relatively rare phenonema (in what sense, where, and at what time of year are not stated). Some readers might find that statement apparently inconsistent with the following chapter describing depressions as essentially frontal phenomena, along with a 'classical' description of warm, cold and occluding frontal structures. Although the difficulties involved are appreciated, it is a pity that the author relies almost entirely on a vintage model for middle-latitude development without any reference to more recent concepts. For example, yachtsmen frequently ask why the strongest surface winds are usually associated with cyclonic circulation patterns. The model used by the author cannot really answer that important question, mainly because it insists on describing development of the surface circulation in terms of a geostrophic response *due* to changes in pressure, without being able to account for the pressure change itself. It also puts too much emphasis on the role of moisture, given that we now know that latent heat is rarely a major energy source in mature Atlantic depressions. The chapters on weather systems should have given some space to a discussion of the relationship between the intensity of surface development and season, given that this is an important factor to consider when planning sailing activities around the British Isles.

The second half of the book is mainly concerned with the more practical aspects of weather and sailing, covering the interpretation and use of weather forecasts and bulletins, observing weather at sea, coastal and offshore wind variations, weather hazards, and the interactions between wind and tide, and wind and waves. The chapter on using weather bulletins contains a concise but comprehensive account of how to interpret information in shipping forecasts, though I am not sure about the implication here that constructing an isobaric analysis from the forecast and coastal reports is an easy task. In my experience most yachtsmen find it an extremely difficult task except for relatively simple synoptic situations; it is perhaps significant that the RYA syllabuses no longer require that this skill be examined. The following sections on coastal and offshore variations of surface winds (including sea-breezes) present highly simplified but nevertheless quite detailed descriptions of factors influencing the type of sub-synoptic wind variations which are of special relevance to coastal sailing, and clearly reflect the author's expertise and practical sailing experience. Most yachtsmen should find these sections fascinating reading, and thus be encouraged to perceive local weather variations as being consistent with, rather than exceptions to, the general synoptic conditions described in weather forecasts.

Overall, the book is clearly written and well produced, with attractive illustrations and plenty of clear line diagrams. Better use might have been made of some of the illustrations through the addition of suitable captions, and the examples at the end of the book might have been extended to include short descriptions of coastal weather conditions as might be observed in association with the analysed weather maps. A course direction given in the first example as 'SW' should read 'SE' to make sense. However, these are minor criticisms, and despite my reservations concerning some of the background material, I believe that the book does on the whole succeed in presenting meteorology at just about the right level for the intended readership, while at the same time giving a more than adequate coverage of most essential topics.

M.A. Pedder

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Prediction of solar radiation on inclined surfaces, edited by J.K. Page (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1986. £59.50, US $85.00, Dfl 180.00) presents methods for the mathematical prediction of values of solar radiation falling on inclined planes under clear conditions in

climates of differing atmospheric clarity and also under overcast conditions. The chapters are a collection of individual European research projects and the whole programme has been extensively checked against practical measurements of actual inclined surface radiation in Europe. Instructions for the manual calculation of the solar radiation are included along with other applications of the European Community Solar Radiation Model.

Oceánic whitecaps and their role in the air–sea exchange processes, edited by E.C. Monahan and Gearóid MacNiocaill (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1986. £40.25, US $64.00, Dfl 145.00) comprehensively describes the current state of knowledge about one of the most elusive physical features of the ocean surface — the whitecaps which form when a wave breaks. Among the many whitecap-related topics treated are wave-breaking, the sub-surface bubble clouds, and the production of sea-salt aerosol as a result of the bursting of whitecap bubbles. The role of whitecaps in sea surface electrostatic charge separation and in air–sea gas exchange are discussed, as is the effect of whitecaps on the remote-sensing signatures of the sea surface. Over 20 papers are included, which were presented at the first International Whitecap Workshop.

Cloud investigation by satellite, by R.S. Scorer (Chichester, Ellis Horwood Ltd, 1986. £39.50) consists of over 600 pictures and photographs which illustrate the language of satellite imagery of the atmosphere. The introductory chapters include a review of the mysterious Channel 3, and discussion on desert dust and sea-glint designed to help interpret the pictures which accompany the text. There are basic discussions of cellular convection, fog and stratus, cirrus, mountain waves, cyclones and anticyclones; and treatment of regional phenomena with individual and peculiar flow patterns, as well as aircraft and ship trails.

An introduction to the theory of climate, by A.S. Monin (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1986, £45.75, US $64.00, Dfl 165.00) presents, in a concise form, the basic concepts, ideas and methods dealing with the contemporary physical theory of climate. An important part of the book is devoted to the discussion of mathematical models related to the climatic system as a whole. Other subjects such as the transfer of radiation in the atmosphere, carbon dioxide, aerosol and ozone cycles, stratospheric circulation, oceanic thermocline, upper layer of the ocean, filtration of moisture in the ground, sea ice, etc. are also discussed in relation to climate. This book will be of value to specialists and graduate students in many different fields.

The atmosphere and ocean: a physical introduction, by N. Wells (London, Philadelphia, Taylor and Francis Ltd, 1986. £15.00 paperback, £29.00 hardback) is an introduction to the physical processes of the atmosphere and ocean for science students. Both systems are described and compared, and examples are given of how the atmosphere and ocean interact. The diverse concepts and ideas of meteorologists, atmospheric physicists and oceanographers are brought together into a single account of the environment, placing the emphasis on physical ideas and mechanisms rather than on mathematics, and thus providing the student with a much better understanding of the atmosphere and the ocean, and an appreciation of their close relationship.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

Sharp monochrome photographs on glossy paper are preferred: colour prints are acceptable but the use of colour within the magazine is at the Editor's discretion. In either case contrast should be sufficient to ensure satisfactory reproduction.

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Meteorological Magazine

October 1986

Vol. 115
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CONTENTS

Page

Experimental monthly long-range forecasts for the United Kingdom. Part I. Description of the forecasting system. C.K. Folland and A. Woodcock 301

Sea surface temperature images from Advanced Very High Resolution Radiometer (AVHRR) data. R.W. Pescod, R.W. Saunders and J.R. Eyre 318

An account of the International Conference on Polar Lows, Oslo, 21–23 May 1986. P.R. Jonas 325

Prolonged clear air turbulence over the British Isles on 4 September 1985. L.A. Hisscott 329

Notes and news

Workshops about the middle atmosphere 332
Advisory group on greenhouse gases 332
Formation of an Association of European Climatologists 333

Reviews

Fields, currents and aerosols in the lower troposphere. R. Reiter. *C.G. Collier* 333
Weather at sea. D.M. Houghton. *M.A. Pedder* 334

Books received 335

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